**DEVELOPING A TOOL FOR THE LOCATION
OPTIMIZATION OF THE ALERT AIRCRAFT WITH
CHANGING THREAT ANTICIPATION**

THESIS

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Abstract

The threat to the airspace is posed by the outside world in conventional terms as well as hostilities from within the airspace such as hijacked aircraft. Alert aircraft are located with the sole responsibility of responding to any incident.

Different regions of the airspace may have different alert states depending on current intelligence input. Due to non-constant states of threat level, the Turkish Air Force must deploy aircraft to cover the more sensitive regions with a greater number of aircraft with a relatively short response time.

This research deals with the problem by developing a tool for the location optimization of the alert aircraft. The tool can adapt to changes in threat anticipation while meeting the objectives of the alert network. Thus, a new location model with backup coverage requirements was formulated, and an interactive tool is developed that is capable of generating the aircraft locations for different user-defined threat anticipation.

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DEVELOPING A TOOL FOR THE LOCATION OPTIMIZATION OF THE ALERT AIRCRAFT WITH CHANGING THREAT ANTICIPATION

I. Introduction

This research deals with the problem of locating alert aircraft in order to protect Sovereign Turkish Airspace. A tool is developed for this purpose. The tool is able to adapt itself to changes in threat anticipation while meeting the objectives of the alert network.

Initially, a brief introduction to Turkey and the Turkish Air Force (TuAF) is presented. This introduction is then followed by the background of the problem. The chapter concludes with the research objectives, scope of the study, assumptions and limitations.

1.1 Turkey and Turkish Air Force

Turkey is a democratic, secular, unitary, constitutional republic located in south-eastern Europe where continents meet. The political system was established in 1923 under the leadership of Mustafa Kemal Atatürk, following the fall of the Ottoman Empire in the aftermath of World War I. Since then, Turkey has become increasingly integrated with the West through membership in organizations such as the Council of Europe since 1949, North Atlantic Treaty Organization (NATO) since 1952, Organization for Economic Co-operation and Development (OECD) since 1961, Organization for Security and Co-operation in Europe (OSCE) since 1973 and the Group of Twenty Finance Ministers and Central Bank Governors (G-20) since 1999. Turkey has been an associate

member of the European Union (EU) since 1963, having reached a customs union agreement in 1995. Full membership negotiations with EU began in 2005.

The area of Turkey is 814,578 square kilometers (302,535 square miles). Shaped almost rectangular, the width of the country is 1,565 kilometers and the length is 680 kilometers. Eight countries border Turkey: Bulgaria to the northwest; Greece to the west; Georgia to the northeast; Armenia, Azerbaijan (the exclave of Nakhichevan), and Iran to the east; and Iraq and Syria to the southeast. The Mediterranean Sea and the Turkish Republic of Northern Cyprus (TRNC) are to the south; the Aegean Sea is to the west; and the Black Sea is to the north. Separating Anatolia and Thrace are the Sea of Marmara and the Turkish Straits (İstanbul and Çanakkale), which are commonly recognized to delineate the border between Asia and Europe, thereby making Turkey transcontinental (Figure 1).

Figure 1 – Location of Turkey and Neighboring Countries

Due to its strategic location astride two continents, Turkey's culture has a unique blend of Eastern and Western tradition. A powerful regional presence in the Eurasian landmass with strong historic, cultural and economic influence in the area between the European Union in the west and Central Asia in the east, Russia to the north and the Middle East to the south, Turkey has come to acquire increasing strategic significance (Wikipedia, 2008b).

The Turkish Air Force (TuAF), having been founded in 1911, is one of the oldest air forces in the world. It operates one of the largest combat aircraft fleets in NATO. The fighter jets can participate in operations and exercises throughout the world, supported by the TuAF's long-range in-flight refueling capability.

The missions of TuAF include the ability to conduct various types of operations such as peace support, crisis management, counter terrorism, small scale strikes, humanitarian aid as well as conventional war.

The Turkish Air Force has taken part in several operations including the Balkan Wars (1912-1913), First World War (1914-1918), Turkish War of Independence (1919-1922), Korean War (1950-1953), Cyprus Peace Operations (1974), Operation Provide Comfort (1991-1996), Operation Deliberate Force (1995), Operation Northern Watch (1997-2003), Operation Allied Force (1999), Operation Enduring Freedom (2001), Operation Iraq's North (2007-2008) and Operation Sun (2008) (Wikipedia, 2008c).

1.2 Background

The Turkish Air Force is assigned the mission of protecting Sovereign Turkish Airspace. The threat to the airspace is posed by the world beyond its borders in conventional terms as well as hostilities from within the airspace, such as hijacked aircraft.

The first threat may be described as airspace problems with neighbors. There are airspace related problems between Greece and Turkey as well as the Western Thrace Turkish Minority problem and several Aegean Sea related problems. There were 38 Turkish Airspace violations in 2007; 36 of these were by Greece (Turkish Armed Forces, 2008a), and there were 386 interventions by the Greek Air Force to Turkish aircraft flying in international airspace over the Aegean Sea (Turkish Armed Forces, 2008b).

It has been noted that "For the airspace related problems, the core of the conflict is the persistent abuse of Flight Information Region (FIR) responsibility by Greece." (Turkish Ministry of Foreign Affairs, 2008b).

FIR is a term that is used by the International Civilian Aviation Organization (ICAO). Article 3/a of the ICAO Convention says "This Convention shall be applicable only to civil aircraft and shall not be applicable to state aircraft". However, Greece persistently claims that the aircraft flying in the international airspace over the Aegean Sea is a violation of the FIR. Although there is not such term as 'violation of FIR', the image that Greece is trying to create in people's minds is that Turkish aircraft are violating Greek airspace. The Turkish aircraft are flying in international airspace which is

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not different from flying over the Atlantic Ocean. The Greek perception of FIR is as a defense perimeter and this abuse of the term is the core of the problems.

The other problem related with the airspace is the Greek claim of 10 miles of breadth of national airspace. In international law, the boundary of territorial sea of a state also is the boundary of the airspace. Greece declared in 1931 that her airspace is 10 miles whereas her territorial sea is 6 miles. This claim made Greece the only country in the world who assumes different borders for the sea and for the air. This claim is not internationally recognized. Most Greek claims about the violation of airspace concern the flights of Turkish military jets within the 6-10 NM international airspace (Turkish Ministry of Foreign Affairs, 2008b).

These problems are expected to continue in the near future despite efforts spent on a permanent solution between the two neighbors. Therefore, the western region of Turkey is categorized as the problematic area for airspace protection. Also, the northern, eastern and southern regions are subjects of concern regarding potential airspace violation.

The second type of threat, terrorism, whether carried out individually or cooperatively, poses a serious threat to peace and security. Turkey is under the threat of terrorism as are other sovereign states from extremists and terrorist organizations.

Terrorism can be defined as "Terrorism is the use or the threat of the use of violence, a method of combat or a strategy to achieve certain targets, that it aims to induce a state of fear in the victim, that it is ruthless and does not conform with

humanitarian rules, and publicity is an essential factor in the terrorist strategy." (Turkish Ministry of Foreign Affairs, 2008a)

Terrorists tend to target the organizations or activities that will create the most anarchy, chaos and unrest. The targets may be national or international summits, strategic facilities, sports organizations, etc. Airspace protection in this sense is very important because targeting such activities or organizations from the air is an option for the terrorists which may be more destructive than most other means of attack.

Hostility from within the airspace is a matter of concern due to its potential to go undetected until the terrorists reach their target. Hijackings or hijacking attempts have taken place on Turkish aircraft since 1972; the total number to date is 18 (Wikipedia, 2008a).

Due to all these facts, necessary precautionary measures must be taken. These measures include detection, interception, identification and prevention. From the time when an aircraft is detected, proper identification is required before the unknown intruder is described as hostile. Although air defense is not solely provided by aircraft, aircraft are the main method to intercept and identify the intruder, and they take the appropriate measures in case of a hostile act instantly and with a high probability of success. There are several set standards for the overall process including, but not limited to, identification procedures, interception procedures, response time requirements, etc. After the identification of the intruder, proper measures are taken by the alert aircraft upon orders from the appropriate level of authority.

1.3 Problem Statement

Considering all internally and externally oriented threats, the TuAF maintains alert aircraft on duty continuously in peace time. The airspace is constantly watched. In case of any intrusion from inside or outside of the airspace, units with appropriate clearance scramble the on-duty aircraft for intercepting the intruder and nullifying the effectiveness of any possible hostile action.

Because of these threats posed to Turkish airspace, the national airspace alert state may vary from region to region at any given time, depending on current intelligence input. Each alert state requires a different level of airspace protection in terms of response time and number of responding aircraft.

The alert network objective is to cover the entire airspace such that the alert state response requirements for all regions are satisfied. The regions may also have backup coverage requirements with a different alert state than the primary coverage alert state. The aircraft that satisfy the primary alert state requirements cannot satisfy the backup alert state requirements. Additionally, the primary and backup aircraft cannot be located at the same base.

When the anticipated threat to a region is changed by the decision makers using intelligence inputs, the primary and backup alert states change for that region. Due to non-constant states of threat level in different regions of Turkey, the Turkish Air Force must deploy aircraft to cover the more sensitive regions with a greater number of aircraft with a relatively short response time. Therefore, the Turkish Air Force requires a

dynamic tool that can locate the alert aircraft for different threat anticipations while meeting the alert network objectives.

1.4 Research Question

The research question applicable to this thesis is:

What is the optimum location of the alert aircraft such that the number of aircraft is minimized and the alert network objective is met?

An objective of the research is development of a tool for answering the research question for different user-defined threat anticipations. The alert states and the boundaries of regions for protection may change as well as the aircraft inventory and airbase availability.

Analyzed in a more systematic way, the objectives are:

- Location optimization

- Achieving the objectives of the alert network

- Adaptation to potential changes in the threat anticipation

The primary objective of location optimization is minimization of the number of alert sites. Secondary objectives may be:

- Minimization of the maximum response time for any site in the network for both primary and backup coverage requirements,

- Minimization of overall or average response time for both primary and backup coverage requirements.

1.5 Scope and Limitations

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Turkish Air Force or the Turkish Government.

This research deals with the problem of locating the alert aircraft in an airbase network with certain performance goals; however, the alert network location decision is strategic in nature and requires consideration of other factors than achieving performance goals. These other factors include policy, cost minimization, personnel and equipment requirements and susceptibility to sabotage. The scope of this study is limited to performance and the primary consideration of this research is optimization of performance parameters of the alert aircraft such as response time objectives set forward by the decision makers.

1.6 Assumptions

Several assumptions are made in this research:

- The research does not differentiate between two aircraft with the same airspeed. There are two parameters that have an effect on the analysis: the airspeed of the aircraft and the time from the scramble order until the aircraft climbs to interception altitude.

- Once the aircraft takes off, it is capable of intercepting the intruder.

- There is no fuel consideration. As the alert aircraft that can intercept the intruder the soonest is scrambled, its fuel will be sufficient to complete the mission. If there is a fuel problem after the execution of the mission, the alert aircraft can land at the closest available airbase and does not necessarily need to return to its own base.

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- No airspace restriction exists for the alert aircraft. It flies a direct route to its target.

1.7 Summary

This chapter presented information about the scope of the study and the background of the problem. Research objectives are systematically analyzed. Limitations and the assumptions are stated. The second chapter discusses the history of location problems and covers the details of location problems, formulations and solution techniques. The third chapter deals with the methodology for the formulation and solution of the problem. In the fourth chapter, the user's guide for the tool developed is presented. Results and analysis are investigated in the fifth chapter. In the final chapter, recommendations are made and future research possibilities for this study are reviewed.

II. Literature Review

2.1 Introduction

The solution of location problems helps decision makers choose locations for facilities such as public libraries, schools, factories, hospitals, distribution centers, air defense units, emergency warning sirens, fire stations, and airbases. Two basic variables of such problems are the available locations and the method of selection (Plastria, 2002).

There are several reasons for the importance of the problem type. First of all, these problems are strategic in nature, due to the initial investment and long term effect of locating a facility. In most of the cases, once the facility is built, it is not reasonable to relocate the same facility in the near future because the establishment of a facility represents a large investment. After opening a facility, its location can have a major impact on its market share. For instance, a shop on Broadway Street in New York City will have more demand and therefore market share than an urban shop in a neighboring suburb. On the other hand, the fixed cost for the shop on Broadway Street is relatively higher. Analysis regarding the selection of the location is therefore strategic for the shop. Secondly, location problems are a part of life and are frequently encountered. From individuals to large industries, people deal with such problems in order to maximize the benefit and gain. Third, the effect of the location of a facility is not only economic but also environmental as well. Therefore, in addition to considering the benefits of facility location, these types of problems should involve minimization of environmental damage. Fourth, the location problems are specific in structure. The parameters of one location problem are different from those of other location problems. Thus, there is no general

problem model that can be applied to all problem instances. Finally, finding the optimal solution of a location problem is extremely difficult. The computational complexity of the problem type makes finding the optimal solution a challenge with the available theoretical and technological tools. Therefore, efficient formulation and implementation is important and necessary to find an optimal solution (Current et al., 2002).

Dating back to the 17th century, people have dealt with location problems. Early contributors mainly focused on the geometry in the Euclidean plane. The emergence of modern location problems and solution techniques has occurred since the 1950s (Eiselt, 1992). Baumol and Wolfe (1958) offered a mathematical programming formulation and approach for the warehouse location problem on a network. They were the first to use the computer to solve a location problem of any kind (Revelle, 1997). Hakimi's proofs (1963, 1964) then followed. Hakimi showed that the optimum distribution of p switching centers in a communication network is at a p median of a corresponding weighted graph. Today, the number of articles concerning location science has flourished.

2.2 Location Models

The general problem is to locate new facilities in order to optimize an objective function. The basic facility location problems are the set covering problem, maximal coverage location problem, p-center problem, p-median problem, p-dispersion problem, hub location problem, quadratic assignment problem, backup location problem types and multiple objective location problems (Current et al., 2002).

2.2.1 Set Covering Location Problem (SCLP)

One of the first location problems was the SCLP by Toregas (1971). In this problem, there is a set of demand points and a set of candidate points. The facilities that are established at the candidate points satisfy the demand at the demand points. The objective of the SCLP model is to minimize the number of facilities established while making sure that all demand is satisfied. The number of facilities to be located is not fixed. The answer to the problem gives the number of facilities to be established. SCLP is classified as NP-Hard (Gayer and Johnson, 1979).

2.2.2 Maximal Covering Location Problem (MCLP)

In the SCLP, the assumption is that all the demand points must be covered; however, this is not necessarily the case in several problem instances. For example, if the demand is not a vital service like an ambulance service, then it might not be necessary to cover all the demand points. For example, a library which is planned to be opened in a new neighborhood must be located such that the number of readers in the walk-distance perimeter is maximized. However, we do not necessarily cover all the readers in the area due to the limit on the number of facilities to be built. There is a variety of reasons for the restriction on the number of facilities; however, the most encountered one is the lack of financial resources. In these cases, maximizing the coverage is the primary objective. There are a certain number of facilities to be located and each facility has a critical coverage distance. The objective is to maximize the demand covered. The maximal covering location problem was formulated by Church and Revelle (1974) to address the

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planning situations which have an upper limit on the number of facilities to be located.

MCLP is also classified as NP-hard (Mediggo, Zemel and Hakimi, 1983).

2.2.3 *P*-Center Location Problem

For both SCLP and MCLP problem types, the coverage range of a facility is fixed and cannot be changed. Although this is true for several problem instances in location science, the minimization of the distance may be the objective as well. The *p*-center problem which was formulated by Hakimi (1964, 1965) minimizes the maximum distance that any demand point is from its closest facility. The number of facilities to be located is *p* and predetermined. The *p*-center problem approach has been used especially to locate emergency facilities (Chhajed, 1993).

There are two common types of *p*-center problems: the vertex *p*-center problem and the absolute *p*-center problem. In the vertex *p*-center problem, the set of candidate points is the nodes. The absolute *p*-center problem allows locating the facilities on the arcs between the vertices. Both problem types can be either weighted or unweighted.

The computational complexity of the vertex *p*-center problem with fixed *p* value is *O(Np)* because each possible set of candidate points are enumerated. For variable values of *p*, the problem is NP-hard (Garey and Johnson 1979).

2.2.4 *P*-Dispersion Location Problem

For all of the models mentioned above, the objective is to keep the demand points close to the facilities. On the other hand, the objective of *p*-dispersion problem is to maximize the distance between the facilities. This type of problems arises especially in

military applications where the separation of facilities decreases the probability of being selected as a target and lessens the enemy attraction.

2.2.5 *P*-Median Location Problem

Some location problems in the private sector deal with minimization of total travel distance between the open facilities and the demand points. The number of facilities to be located is fixed *a priori*. The type of problem where the objective is to minimize the total distance between the demand points and the facilities to which they are assigned is the *p*-median problem. The minimization of the total distance implies the minimization of average distance between the demand points and the facilities to which they are assigned; the total distance is simply the multiplication of the average distance by the number of facilities (Hakimi, 1964, 1965).

2.2.6 Hub Location Problem

When flying over long distances, commercial airlines usually take the traveler to a center location and then route the traveler to the final destination. This commonly encountered situation is an example of hub location. The airline first flies the customer to their hub location. Hub location problems are generally used in transportation and telecommunication systems. Hub locations are switching locations on routes. Connecting every single node in the network with any other node is expensive; a hub network allows transportation from each node to every other node through intermediary node. This decreases the number of arcs in the network which in turn minimizes the cost. Thus, all the customers at each node can be transported to their final destination less expensively via hub locations (Campbell, 2002).

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2.2.7 Quadratic Assignment Location Problem

In this special type of assignment problem, the objective function is quadratic, and it is possible to flow from each candidate point to any other candidate point. The objective is to minimize the sum of the travel distances of flows (Current et al., 2002).

2.2.8 Multi-Objective Location Problem

The objective functions of the problems that are mentioned above are either the minimization or the maximization of a value: distance or cost; however, both of these values may simultaneously be the objective. A company, for instance, may want to maximize customer satisfaction while minimizing cost. These types of problems require multi-objective location modeling, and the objectives may be supporting or contradicting. There are several reasons for contradiction, such as risk versus profit. Additionally, interest in environmental factors is increasing and is often another main parameter in multi-objective problems (Erkut, 1995). The objectives are generally classified as the cost minimization problems, demand oriented problems, profit maximization problems and environmentally concerned problems (Current, 1990). The first paper about multiple objective problems was in 1978 by Cohon, ReVelle and Current, and was an application of a multi-objective facility location model to power plant siting in a six-state region of the U.S (Cohon et al., 1978).

Although all possible combinations of objectives are not reviewed in the literature, several examples exist. As of 1990, Current, Min and Schilling reviewed 71 different multi-objective papers and concluded that the largest class is cost minimization, which also included distance minimization (Current et al., 1990). One of the early

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instances of this type is by Current, ReVelle and Cohon in 1985 where they investigate

the optimality for the maximum coverage and the shortest path simultaneously (Current

et al., 1985).

The objectives of a multi-objective location problem may be simultaneously

optimized. Another common method is to hierarchically define the precedence of the

objectives and deal with them sequentially. They are solved one at a time according to the

importance level set forward by the decision makers.

2.2.9 Backup Coverage Location Problems

Backup coverage, which is defined as the second coverage of a demand node, is

suggested as a decision criterion in the location of emergency services on a network by

Hogan and ReVelle (Hogan et al., 1986). They formulated two backup coverage

problems: backup coverage 1 (BACOP1) and backup coverage 2 (BACOP2). According

to their model, there are two critical distances: inner and outer distances. The inner

distance coverage is solved as a set covering problem and all the demand points must be

within the inner distance of a candidate point. Maximum set covering problem is solved

for the outer distance. The demand points in outer distance range do not require coverage.

The number of demand points covered within outer distance is maximized in the

problem. The outer distance is different from the inner distance. A demand point is

covered by a backup when an additional candidate point covers the demand node.

Therefore initially solving the set covering problem and then maximizing the number of

doubly covered areas is the formulation for BACOP1. For the BACOP2 formulation, it is

not necessary to cover all demand points. Neither of the formulations by Hogan et al.

necessarily requires second coverage for all the demand points but rather maximizes the number of points that are covered twice.

A different model formulation was developed by Pirkul and Schilling in 1988. Pirkul and Schilling's model requires second coverage of every demand point. The model is a generalization of SCLP and BACOP1. The model also added the capacity of the candidate points into the formulation.

In Pirkul and Schilling's model, the minimum number of facilities to satisfy the demand is determined; however, the number of vehicles at each facility is not known. The variables used in Pirkul and Schilling's formulation are binary and the decision is whether or not to open a facility. For this reason, an open facility at a candidate point can satisfy any demand point within its range, regardless of the number of vehicles located at the facility. This is a limitation of the model; some demand points may require more than one alert vehicle (in this research, the vehicle is alert aircraft). Therefore, a facility might not satisfy a demand point if the alert vehicles are less than that required at the demand point.

In Pirkul and Schilling's model, a demand point cannot be served a second time by the facility to which it is primarily assigned. Therefore, the model does not assign the primary and the backup coverage responsibilities to the same facility. This is applicable when the variables can take on binary values. In order to determine the number of alert vehicles located at the candidate points, the variables must take on integer values. In that case, Pirkul and Schilling's model can locate alert vehicles at the same candidate point for primary and backup coverage.

2.2.10 Other Location Problems

Modeling of location problems is not restricted to the aforementioned models. The time variable, for instance, is never mentioned. Also, models may sometimes adapt themselves to changing demand. When the time is included in the model, then dynamic programming is required. The candidate points may satisfy demand for a certain time, and then the demand point may be served by another candidate point at a different time.

Another aspect of the location problem is the probabilistic nature of the problems. For all the problems considered, the demand is known with certainty; however, probabilities may be associated with demand points. It these situations, stochastic processes must be included in the models.

2.3 Model Structures

The problems may be divided into three subcategories according to their structure types: planar models, network models and discrete models. The models mentioned in the previous section can be classified in any of the three structure types with little modification.

The core difference between the three types is the definition of distance (Chhajed, 1993). Distance is a numerical description of how far apart objects are; and there are different methods to model the distance between two points. Four general types of distance modeling are used in the literature. The first is the 2-norm Euclidean distance which may be viewed as the voice traveling distance between two points. Second is the rectangular/rectilinear distance which restricts proceedings in directions that are parallel or perpendicular to each other. An example of this is traveling from one point to another

using the square blocks of a city. Therefore, this is sometimes referred to as taxicab norm or Manhattan distance. Rectilinear distance is Euclidean distance in 1-norm. The third distance modeling is road travel distance. This is the distance that a person or a vehicle travels from one point to another via a network of roads or routes. This model is used in Dijikstra's algorithm. The fourth and the last modeling type to be considered is the distance that is obtained when the locational space is a sphere also known as is the great circle distance. There are three commonly used formulations to find the distance between two points on a sphere. They are the law of cosines, the Haversine formula and the Vincenty formula (Wikipedia, 2008d). The main difference between the formulas is the elimination of rounding errors in some extremities of the world such as the south and north poles.

2.3.1 Planar Structure

In methods using a planar structure, the distance is often modeled as the Euclidean distance or the rectilinear distance. Spatial demand is covered with the candidate points found in the continuous plane. The number of demand points and the number of candidate points are infinite. The demand is satisfied if it is located within a certain radius of any candidate point. Every candidate point is usually modeled as a circle and the problem is formulated by positioning several circles on a plane. The radius of the circles can change depending on the type of the problem. For instance, for the p-center problem, the radiuses of the circles are not fixed, but the number of the circles is given. In this case, the problem involves minimizing the radius of the circles while meeting the problem specific constraints. For the set covering location problem, the circle's radii are

fixed; the number of circles required to cover the demand area is minimized. Such an application for locating emergency warning sirens is formulated by Current and O'Kelly (1992). The *p*-center location problem in a given square area is reformulated by Suzuki and Drenzer (1996) and solved using heuristic methods. The same problem is also addressed for arbitrary shaped areas by Ezra and Handler (1994); they use an interactive human-computer approach. The user inspects the results if the optimal point is still feasible after relaxing of the problem.

When a problem is modeled using the planar structure, the problem is generally difficult to solve; therefore the continuous demand is discretized as single points. This abstraction is called demand point aggregation. The demand in an area is represented with a single point with a given weight. Although it brings computational efficiency and ease of solution, replacing continuous demand with discrete demand has some drawbacks (Francis et al., 2002). Unless the region under consideration is unbounded, the set of feasible solutions is finite after the aggregation of demand points. Unfortunately, there is an inherent error due to aggregation. The distance from each single point in continuous space to the candidate points changes with this aggregation. Error bounds are investigated and an error minimization approach, called distance correction, is proposed (Drenzer and Drenzer, 1997). This approach requires addition of 0.16 times the sub-area, from which the demand point is aggregated. It has been shown that as long as the demand points and the candidate points are far from each other, this correction greatly reduces the error due to abstraction.

2.3.2 Network Structure

A network consists of a collection of nodes and arcs where each arc has a pair of nodes as its end points. The distance between two points is the shortest travel distance in the network. In network models, the demand points are located on the network nodes and the candidate points are to be located at points on the network (Chhajed, 1993).

Maximum flow problems, shortest path problems, and transportation problems are generally modeled as network models due to the problem structure. Many hub locations also are modeled as network models.

2.3.3 Discrete Structure

The number of demand points and the number of candidate points for discrete models are finite. The distance is modeled according to the specific problem requirements; there is no restriction on the modeling type. As long as the level of abstraction permits it and the solution is kept valid, both planar and network models can be converted into discrete models. The discrete problems are often modeled as mixed integer linear programs (MILP).

2.4 Solution Techniques

There are three common solution techniques: exact methods, approximation algorithms and heuristic methods. Exact methods determine an optimal solution. Good approximation algorithms give a feasible solution in polynomial time with an objective function value that is close to the optimal solutions. Heuristics, on the other hand, find a 'good' solution in a 'reasonable' time but do not guarantee of feasibility or closeness to optimal solution. As a result, there are some techniques for evaluation of heuristics with

respect to bounds on the problem, worst-case or statistical analysis. There are advantages and disadvantages for each method. Each of the methods is presented below.

2.4.1 Exact Methods

Exact methods search for the optimum value of a function. Since the advent of the simplex method, several algorithms have been proposed for solving optimization problems. These algorithms generally differ from each other according to the input value types, desired output value types and formulations. Exact methods have several subcategories such as linear programming (LP), mixed integer linear programming (MILP), non linear programming (NLP) and dynamic programming (DP). One of the earliest exact method algorithms to solve an LP problem is the simplex method. The simplex method moves on the boundary of the feasible region searching for an optimum point. The search continues until no further improvement can be achieved. Another method to solve the LP is interior point methods. These methods move toward the boundary of the feasible region. The main difference between the simplex method and interior point method is that interior point methods traverse the interior of the feasible region while the simplex method traverses the boundary.

Integer programming problems are a special case of LP where all variables are required to be integer. The solution techniques for these problems are different from LP. When some variables are required to be integer but others are not, the problem is formulated using the MILP. MILP problems are solved using explicit enumeration, implicit enumeration and cutting plane algorithms.

If the set of feasible solution is finite, one may enumerate each and every single solution within the solution space and find the optimum value. This is not an efficient method of solving with the problem, especially when the dimension of the problem (or number of decision variables) is relatively large. The second method is implicit enumeration, commonly known as branch and bound. The branch and bound method systematically enumerates the feasible solutions such that each iteration divides the solution space into two. Dividing every subspace into two each time leads to one optimal solution which cannot be further improved. Another method is the relaxation method. This approach relaxes the variable bounds or restrictions so that an 'easier' problem with same set of feasible solutions arises. Then solving this problem with relaxed bounds gives the optimal solution that is exactly the same as original problem's optimal solution. Cutting plane algorithms is a special type of relaxation. This method finds the convex hull for the feasible region, and the MILP may then be converted and solved as an LP.

The techniques that are mentioned for exact solutions do not necessarily arrive at unique optimal point. Alternative solution results are infeasibility or multiple optimal solutions. If the problem is ill-defined, then the algorithm may result in unbounded solutions.

2.4.2 Approximation Algorithms

Many location problems are in the class of NP-hard problems. Solving these problems with exact methods is difficult in cases where the size of the problem instance is large. Unlike heuristics, which only find reasonably good solutions reasonably quickly, approximation algorithms have provable solution quality and provable run time bounds.

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In approximation algorithms, one may find a solution that is guaranteed to be a factor multiple of the optimal solution.

For the general facility location problem, there are two common approximation algorithms that use linear programming in order to find a bound on the approximate solution in terms of the optimal solution of the problem. The first one is LP rounding, which is used to solve the set covering location problems as well as the p-median problems in polynomial time with a guaranteed solution with an f multiple of the optimal value (where f is the frequency of the most repeated element in the covering set). The second approximation algorithm is the primal-dual schema. Starting with feasible solutions for both primal and dual problems, this algorithm iterates until both complementary slackness conditions are satisfied. This algorithm approximates the solution in polynomial time with a factor of 3; this implies that the algorithm gives 3 times the optimal value in the worst case.

There are other techniques than these two common ones to approximate a solution for the facility location problem. These include the method of dual fitting for the set covering problem, and parametric pruning approximation algorithm for the p-center problem.

The reader is referred to the book *Approximation Algorithms* (Vazirani, 2003) for more detailed implementations of the aforementioned approximation algorithms.

2.4.3 Heuristic Methods

Heuristic methods are rules of thumb for finding solutions. They do not necessarily guarantee feasibility. These methods are often utilized because exact methods

may not be available or the time required by an exact method may be excessive. The solution provided by a heuristic method is approximate in the sense that it is not guaranteed to be the optimal solution; while it may be very close to an optimal solution, it is generally not possible to determine exactly how close it is. In addition to the solution quality, another important attribute of a heuristic is the time to find a solution. Because some heuristics utilize randomization, the time to reach the solution might need to be given in terms of the average-case time or the worst-case time.

One of the most common heuristics is greedy heuristics. As the name implies, a greedy heuristic 'greedily' takes the best improving result from a set of candidate points. For example, if the objective function maximizes the profit, then the algorithm sequentially selects the available candidate point that improves the objective function value the most. Each time the algorithm 'selects' the best contributor to the objective function, it enumerates the rest of the candidates in the candidate set. Depending on the type and the structure of the problem, the algorithm terminates when it reaches the desired number of facilities in the solution space or a solution of predetermined quality. Greedy heuristics are classified as greedy-add and greedy-drop. For a p-center problem, the greedy-add algorithm begins with a feasible solution and then selects the facilities that improve the objective function the most. On the other hand, the greedy-drop algorithm selects all of the candidate points and removes the candidates with the least contribution to the objective function until a predetermined number of candidate points remain in the solution set. Although both of the greedy heuristics are effective at

identifying feasible solutions with a modest level of computational effort, they do not consistently produce satisfying results.

After generating an initial solution (that is not required to be feasible), the solution can be improved using an improvement heuristic. One of the early versions of an improvement heuristic is the neighborhood search algorithm. In this algorithm, a neighborhood function is initially defined. The neighborhood function applies a modification to the current solution so that another solution is obtained. One neighboring function for the location problem involves closing a randomly selected facility in the current solution and opening another randomly selected one from those that are not already selected. This may or may not improve solution. The modified solution is evaluated at each iteration and compared with the best solution.

One major problem with the improvement heuristics is that the algorithm may get trapped in a local optima. To prevent this, metaheuristics were developed. These procedures use memory to keep track of the solutions that an algorithm produces. If the solution does not improve for a predetermined number of times, then the algorithm 'jumps' from this solution to another area of the solution space. At each iteration, several neighboring solutions are compared with the current solution; the solution which improves the objective function the most is accepted as the new current solution.

In metaheuristics, the algorithm does not necessarily need to improve the objective function at every iteration; occasionally a worse solution may be accepted with some probability in order to visit different regions of the solution space. This probability could be with respect to how much apart the current solution is from the best known

solution. The current solution is modified in this manner for several iterations or until a termination criterion is satisfied. Algorithm performance highly depends on the neighboring definitions.

2.4.4 Comparison of the Solution Methods

There is no consistent method for selecting the best technique to solve a MILP. The nature of the problem is the driving factor for selection of the solution method for the problem instance.

Exact methods are good for cases where the optimal solution is more important than the time required producing it. Thus, if the size of the problem is not large and there is time available for solving the problem, exact methods are preferred. Approximation algorithms and heuristics, on the other hand, may result in solutions that are not optimal. If the size of the problem is extremely large, exact methods take an unacceptable amount of time. In these situations, approximation algorithms and heuristics can be used. Depending on the problem instance, either method may be preferred. If the approximation algorithm proposes a solution reasonable close to the optimal solution and is 'quick enough' to handle the problem, then approximation algorithms are adequate solution techniques. As the problems already include some generalization and assumptions, the exact solutions do not necessarily represent "real life". Thus, approximation algorithms may produce good results for the real life problems. After analyzing the problem, the size and time requirements may indicate a preference for using a heuristic algorithm. Although in theory they guarantee neither feasibility nor closeness to optimality, there are several practical applications that use heuristics and

give satisfactory solutions to the problems. Another benefit of heuristic algorithms is that their solutions can be used for the starting point for the exact methods which may increase speed of locating a solution for the exact methods. Technique to use for a given problem is a difficult task. The selection process depends on the problem instance and desired level of output and available timeframe.

2.5 Relevant Past Studies

Similar problems have been previously addressed by several authors. Search and rescue stations in the Aegean and Mediterranean Regions of Turkey were located using the maximal coverage location problem (Basdemir, 2000). In that study, some areas are out of coverage of any possible facility location; therefore, a maximal coverage solution is preferred.

The optimal location of Continental United States Strip Alert Sites Supporting Homeland Defense has also been addressed (Eberlan, 2004). In Eberlan's study, p-center and p-median problems are solved with no backup coverage requirement.

The Tanker Employment Problem is modeled as a capacitated facility location problem and solved using heuristic methods (Miller, 2005). The similarity of Miller's research to the current research effort is in the computer coding techniques of the algorithms. In particular, Miller's research utilized VBA in order to address different instances of the problem and produce feasible solutions.

Another research effort involved Surface-to-Air Missile Requirements for the Western and Southern part of the Turkish Air Defense System. This problem was solved

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using both the set covering problem and the maximal coverage location problem (Alkanat, 2008).

The current research study differs from previous studies in three major aspects. First, the formulation methodology of the current research is different from the previous studies; this is presented in detail in Chapter 3. Second, the ability to dynamically change the problem is accommodated. This research enables the decision maker support teams to change the input data and rapidly generate solutions for different cases. The final area which distinguishes this research from previously conducted research is in the area of threat anticipation.

2.6 Summary

Location problems are strategic in nature and draw the attention of both the governments and commercial business. The appropriate location of a facility could significantly improve the facility's functionality. On the other hand, poorly locating a facility can cause loss of productivity and/or market share.

A brief summary of location models was introduced in this chapter. The common model structures were then investigated and solution techniques were reviewed. The next chapter introduces the methodology, which is based on the models discussed this chapter.

III. Methodology

3.1 Introduction

The Turkish Air Force needs an algorithm with a user-friendly interface that can locate alert aircraft based on different threat anticipations. These locations need to satisfy the alert network objective, which is to cover all the airspace such that the alert state response requirements for all regions are satisfied. The regions may also have a backup alert state as well as a primary alert state. The aircraft that satisfy the primary alert state requirements cannot satisfy the backup alert state requirements. Additionally, the aircraft assigned for the primary alert coverage for a region cannot be located at the same base as the aircraft that provide backup coverage for the same region.

This research must answer the question:

What is the optimum location of the alert aircraft such that the number of aircraft is minimized and the alert network objective is met?

The objective of the research also includes developing a tool for answering this question for different user-defined threat anticipations. The alert states and the boundaries of regions for protection may change as well as the aircraft inventory and the airbase availability.

Therefore, the objectives of the algorithm and user-interface are:

- Indicate the optimal location of aircraft

- Achieve the objectives of the alert network

- To be able to adapt to potential changes in the threat anticipation

The first objective mentioned, the location optimization, is related to the formulation of the model. The objective of location optimization is primarily the minimization of the number of alert aircraft. Secondary objectives may be:

• Minimization of the maximum response time for any site in the network for both primary and backup coverage requirements

• Minimization of overall or average response time for both primary and backup coverage requirements

The second objective is to achieve the objectives of the alert network. This objective is met by incorporating several additional constraints into the mathematical model; these constraints is discussed in more detail in Formulation of the Model section of this research.

The third objective, adaptation to potential changes in the threat anticipation, is related to the design of the tool. The alert state changes for a region when the anticipated threat is changed by the decision makers. Thus, the tool must be interactive so that the user has the capability to change the alert state for different regions. The solution generated by the tool has to meet these new alert state requirements. This ensures that the tool is adaptable to different threat anticipations.

3.2 Data

Prior to solving the described problem, various forms of input data are required. The user must input aircraft and airbase information; the tool generates the mathematical model that is specific for the input parameters.

Due to the security classification of the real-world data, generic data is used in scenarios in the fifth chapter.

3.3 Model Structure

Recall there are three model structures: planar models, network models and discrete models. As long as the level of abstraction permits and the solution is kept valid, both planar and network models are usually converted into discrete models. Discrete models are easily modeled as mixed integer linear programs. Since the error due to the abstraction is negligible (see Chapter 2) and does not affect the solution, the model developed in this research has a discrete structure.

Another structural consideration is the manner in which the objectives are modeled. There are typically more than one objective in this type of problem. The objectives of a multi-objective location problem may be simultaneously optimized or hierarchically optimized by defining the precedence of the objectives and dealing with them sequentially. In the current research effort, the objectives are stated in a sequential manner. The primary objective is to minimize the number of alert aircraft while the airspace is protected with respect to alert states; the primary objective cannot be interchanged with either of the secondary objectives. If the primary objective is not satisfied, then secondary objectives cannot be realized.

3.4 Solution Technique

The solution techniques presented in Chapter 2 are exact methods, approximation algorithms and heuristic methods. The facility location problem is strategic in nature.

Once the aircraft are located in peace time to protect the airspace, relocating them would not be cost effective for the Air Force due to facility, personnel and budget constraints. Therefore, solving the problem quickly is not a consideration but finding the optimal solution is the primary concern. Therefore, an exact method solution technique is chosen as the solution methodology.

3.5 Tools for Coding

There are several software packages available for solving mixed integer problems with exact methods. Solvers are commonly utilized in order to solve the mathematical programming problems; there is a diversity of commercially available software. They differ in several aspects: the types of optimization problems that they address, how they define the problem, solution methodologies, the analysis of the results, diagnosis of errors, graphical user interfaces, and problem definition limitations of the software. This research deals with a problem that requires input data from the user. The tool must be interactive such that different threat anticipations can be modeled and solved. Therefore software that has the ability to communicate with the user via graphical user interfaces (GUIs) is required.

Microsoft Excel features calculation, graphing tools, pivot tables and a macro programming language called Visual Basic for Applications (VBA). At the time of this research, it is one of the most common spreadsheet analysis software packages. VBA is an implementation of Microsoft's Visual Basic built into most Microsoft Office applications including Excel. Microsoft Visual Basic is a relatively easy to use programming language because of its graphical development features. By embedding the

VBA into applications, GUIs can be built. With the dynamism that VBA provides, interactive applications can be developed.

Due to these promising features, Microsoft Excel with VBA is selected as the coding platform for the tool. The model can be generated in VBA; however, the solution of the model requires optimization software.

There are several software packages that solve optimization problems. The alternatives that are reviewed in this chapter are: Excel Solver and LINGO.

Excel Solver is built by Frontline Systems and is an add-in to Microsoft Excel. It is a commercial tool which solves optimization problems using Excel data structure. The model is written in the worksheets of Excel. Using a GUI, the inputs are entered in the Excel Solver, and the model is solved and the results are displayed. Excel Solver is easy to access from VBA. One can enter the model and run it using VBA. The user does not need to deal with entering the model to the optimization software when using the tool. One drawback of Excel Solver is that the communication between Excel spreadsheets and VBA slows down the solution process. Solver spends as much as 90% of its time waiting for Microsoft Excel to recalculate the worksheet (Frontline Systems, 2008). Therefore, for large sized problems, Excel Solver is not efficient. Another drawback of the software is the limitations on the number of variables and constraints.

The other optimization software that is considered is LINGO. LINGO is a comprehensive tool designed to build and solve optimization models quickly, easily, and efficiently. It includes a powerful language for expressing optimization models, a full featured environment for building and editing problems, and a set of fast built-in solvers.

Although it has an environment different from Microsoft Excel, the model can be sent from Microsoft Excel to LINGO using VBA and the results can be returned to Microsoft Excel. LINGO does not require Excel in order to solve the problem. This implies that there are faster solution times in LINGO compared to Excel Solver. The drawback of LINGO (according to the author's experience) is that the communication between Microsoft Excel and LINGO does not allow large models. After approximately 2000 variables, Microsoft Excel ceases transferring data to LINGO using VBA. Although the model can be solved using LINGO syntax from the LINGO GUI, the same model cannot be solved when sent from VBA. Each of the optimization software packages has advantages and disadvantages. One common drawback of both is that they require commercial licenses in addition to a standard Microsoft Office software suite.

To overcome some of the limitations, it was decided to capture the problem formulation as a Mathematical Programming System (MPS) file. MPS is a file format for presenting and archiving LP and MILP problems. Excel was used to create the MPS file. Most optimization software including Excel Solver SDK, LINGO and CPLEX and some free optimization codes such as lp_solve can read MPS files. For more information on reading MPS files, the reader is referred to a web page by National Center for High Performance Computing in São Paulo (CENAPAD-SP, 2008). When an MPS file is generated, the user is free to use any optimization software. Also, the new tool developed in this research does not require any license other than Microsoft Excel which is already available on almost all Turkish Air Force computers.

3.6 Modeling of the Problem Parameters

Some parameters of the problem need to be incorporated in the model. These include the aircraft, the candidate points, the demand points, distances and coordinates.

3.6.1 The Aircraft

In the model, each aircraft is assumed to take off with no failure. After take off, the aircraft climbs to the interception altitude; the aircraft then flies on a straight flight path at cruise speed until it intercepts its target. The model assumes that, after the interception aircraft has the capability to execute its mission, it has enough fuel to land at an airbase. The mission execution time cannot be predetermined; however, depending on the situation, the air operation center can scramble another alert aircraft to continue the same mission after the first alert aircraft intercepts the intruder: The modeling of aircraft depends on two parameters that enable us to find the time to reach to the intruder: the time to climb to the interception altitude after takeoff and the level flight speed at the interception altitude. These parameters also aid calculation of the range of a specific type of an aircraft from an airbase.

3.6.2 The Candidate Points

The candidate points are simply all possible airbase and aircraft combinations that are compatible with each other. The tool will allow the user to enter the aircraft information, the airbase information and compatibility table. The model needs the coordinates of the bases as well as the compatibility of the airbases with the aircraft.

3.6.3 The Demand Points

The tool allows the user to input regions and associated alert states. Each region is formed of squares with 20 mile edges. The demand in each square is aggregated and is a vector with the cardinality equal to the number of aircraft required for that region. For instance, Turkish airspace, with 302,535 square miles of area, is represented by 756 demand points. As explained in Chapter 2, a demand point aggregation creates an error; however, for a problem where the candidate points are far apart such as airbases, the error is negligible.

3.6.4 The Distance

For this research, the distance between two points is calculated using the haversine formula (Wikipedia, 2008d). Let ϕ_1, λ_1; ϕ_2, λ_2 be the geographical latitude and longitude of two points and define $\Delta\phi$, $\Delta\lambda$ to be their differences. Let $\Delta\hat{\sigma}$ be the central angle which is computed using:

$$\Delta\hat{\sigma} = 2\arcsin\left(\sqrt{\sin^2\left(\frac{\Delta\phi}{2}\right) + \cos\phi_1 \cos\phi_2 \sin^2\left(\frac{\Delta\lambda}{2}\right)}\right)$$

The distance between the two points equals the central angle multiplied by the radius of the earth: $d = R\,\Delta\hat{\sigma}$, where R is the earth's radius (approximately 3959 miles).

3.6.5 The Coordinates

The tool is interactive; the user either enters coordinates on a map or he/she examines the results of the analysis using a map. The computer uses pixels to address locations on the screen. Due to the shape of the earth, the latitudes and the longitudes do

not change linearly. Therefore, a procedure in the tool is necessary to convert the computer pixels into coordinates.

Rather than attempting to model the shape of the earth, a regression analysis was conducted to display coordinates on the flat computer screen. The scope of the research is limited to Turkey and its neighboring countries; therefore, the regression error must be within reasonable bounds in the area of interest. The latitude and longitude for 70 separate locations (for which the pixels on computer screen are known) were determined. The regression analysis was carried out using 40 of the data points; the remaining 30 data points were used for validation of the regression formula.

The regression analysis resulted in a quadratic function for the prediction of the coordinate for a given pixel on the computer screen. After the regression analysis, the average error between the real coordinate and the regression analysis prediction was 1.28 miles and the maximum error was 2.68 miles. This error is negligible for the current research effort. The data points and the regression results are in Appendix A.

3.7 Preprocessing

The demand points are user defined regions with associated alert states. The candidate points are the compatible aircraft and airbase combinations. The objective is to cover all the demand points with a minimum number of candidate points.

Because the problem is strategic, an uncovered region is not acceptable. Therefore if the coverage cannot be satisfied, then the tool must show the user which regions are not covered. This creates more awareness for the user so that he/she can change the borders of the regions or the associated alert states.

Before starting the solution process, the preprocessing module creates a table of demand points and the set of candidate points that can cover them. After building the table, the algorithm evaluates each demand point. If the demand point requires only primary or backup coverage, at least one candidate point is required; however, if both primary and backup coverage are required, at least two candidate points must exist that can cover the demand point. Therefore, there are 4 types of uncovered regions:

- Backup demand cannot be covered.

- Primary demand cannot be covered.

- Both the backup and primary demand cannot be covered.

- Both backup and primary coverage is required but only one type can be covered.

The preprocessing module of the tool identifies uncovered regions and displays the map to the user. If the user wants to remove the demand points in uncovered regions, the tool automatically removes them.

3.8 Formulation of the Model

Potential methods to model the problem are presented in Chapter 2. First of all, in order to address the primary objective of minimizing the number of alert aircraft such that each region is covered at the respective alert state, the problem must be formulated as a set covering location problem.

If a feasible solution is found for the set covering problem, then alternate optimal solutions could exist for the given number of alert sites. Therefore the optimal solutions that best serves the additional problem objectives will be the preferred problem solution.

At this point, the secondary objectives are reviewed. The secondary objectives may include:

• Minimization of the maximum response time for any site in the network for both primary and backup coverage requirements

• Minimization of overall or average response time for both primary and backup coverage requirements

The first additional objective is the minimization of maximum response time and can be modeled as a *p*-center problem. The optimal solution of the SCLP is the minimal number of facilities to be located and is used as the *p* value for the *p*-center problem.

The second additional objective is the minimization of the overall or the average response time. *P*-median problem formulation can be used to address this problem. As explained in Chapter 2, the *p*-center problem is generally used in order to cover customers in the outspread areas of a region. The objective function is to minimize the maximum distance on the entire network. Therefore, the *p*-center problem locates an aircraft relatively close to the demand points. For this reason, the *p*-center solution causes the alert aircraft to disperse in the network.

The *p*-median problem, on the other hand, minimizes the total distance in the network. In contrast to *p*-center model solution, this causes the selected facilities to be centered in areas of the network. A notional example is in Figure 2; D1 and D2 are

demand points and C1 and C2 are candidate points. The distances on the figure are actual distances.
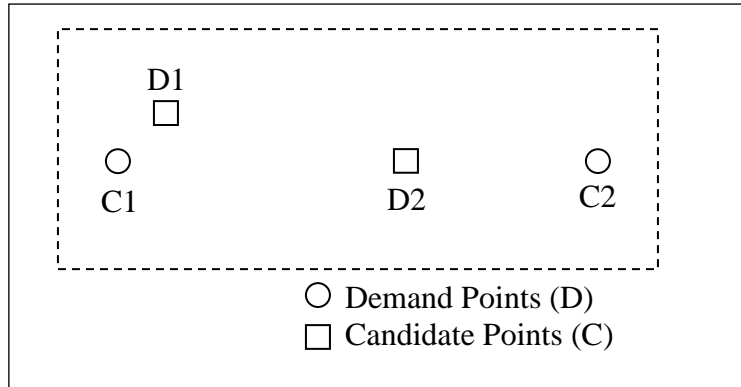
Figure 2 – Notional Example

Assume that both D1 and D2 demand points require 2 units of service. The *p*-center solution for this problem would locate one unit at C1 and one at C2 in order to minimize the maximum distance in the network. However, the *p*-median solution locates both units at C1 to minimize the total distance.

The regions' alert state requirements are defined by the user. Once these requirements are satisfied, further improvement of the maximum response time is not required; however the *p*-center problem minimize the maximum response time. Another problem that arises with the *p*-center problem is that different regions could require different levels of response. For example, if the user defined a region with a response requirement of 60-minute and all other regions require 15-minutes, then the *p*-center problem would locate the aircraft closer to the 60-minute requirement region in order to improve the worst time in the network.

The *p*-median problem, on the other hand, locates the aircraft such that they are closer to the regions that require more aircraft and quicker response time. This implies that the aircraft are located closer to those regions that are more important while maintaining coverage in all other regions according to user defined alert state levels. One other aspect is the cost effectiveness. Locating the alert aircraft in centralized bases is a better option due to personnel and maintenance considerations.

Because of these reasons, the *p*-center problem is eliminated and minimization of total distance is selected as the secondary objective for the problem. The notations used to define the model are as follows:

I = the index and set of demand points;

J = the index and set of candidate points;

A={i|i require primary coverage}

B={i|i require backup coverage}

C={i|i require <u>both</u> primary and backup coverage}

I=(A ∪ B) \ C

S_i = maximum primary covering distance of the ith demand point. S_i is in respect to the alert state response time.

$J_i = \{j \in J \mid d_{ij} \leq S_i \ \forall i \in A\}$ is the set of candidate points j within the coverage distance S_i of demand point i that require a primary coverage}

S_i' = maximum backup covering distance of the ith demand point. S_i' is in respect to the alert state response time.

$J_i' = \{j \in J \mid d_{ij} \leq S_i' \; \forall i \in \mathrm{B}\}$ is the set of candidate points j within the coverage distance S_i' of demand point i that requires backup coverage}

P = number of alert sites to be located (result from primary objective function)

h_i = number of required aircraft for primary coverage at demand point $i \in \mathrm{A}$

h_i' = number of required aircraft for backup coverage at demand point $i \in \mathrm{B}$

Add_Const = the set of additional constraints that are defined by the user to locate some minimum, maximum or exact number of aircraft at certain bases. Their form is any of the following 3 equality/inequalities: $x_v \geq f_v$, $x_v = f_v$, and $x_v \leq f_v$ where v is the selected base and f_v is a fixed value

x_j = number of aircraft located at candidate point j

y_{ij} = number of aircraft located at candidate point j that are assigned to primary coverage of demand point i

z_{ij} = number of aircraft located at candidate point j that are assigned to backup coverage of demand point i

y_{ij}' = 1 if y_{ij} is assigned a number, 0 otherwise

z_{ij}' = 1 if z_{ij} is assigned a number, 0 otherwise

d_{ij} = travel distance between area of interest i and candidate point j

Thus, the mathematical formulation for this problem is:

Minimize $\quad \displaystyle\sum_{j\in J} x_j$ $\qquad\qquad\qquad\qquad\qquad\qquad$ (1.1)

Minimize $\quad \displaystyle\sum_{i\in A}\left(\sum_{j\in J_i} h_i d_{ij} y'_{ij}\right)+\sum_{i\in B}\left(\sum_{j\in J_i} h'_i d_{ij} z'_{ij}\right)$ $\qquad$ (1.2)

Subject to

$$\sum_{j\in J} x_j = P \qquad \text{(only with 1.2)} \qquad\qquad (2)$$

$$Add\_Const \qquad\qquad\qquad\qquad (3)$$

$$\sum_{j\in J_i} y_{ij} \ge h_i \qquad\qquad \forall i\in A \qquad\qquad\qquad (4)$$

$$\sum_{j\in J_i} z_{ij} \ge h'_i \qquad\qquad \forall i\in B \qquad\qquad\qquad (5)$$

$$x_j - y_{ij} \ge 0 \qquad\qquad \forall i\in A,\ \forall j\in J_i \qquad\qquad (6)$$

$$x_j - z_{ij} \ge 0 \qquad\qquad \forall i\in B,\ \forall j\in J'_i \qquad\qquad (7)$$

$$-y_{ij} + h_i y'_{ij} \ge 0 \qquad\qquad \forall i\in A,\ \forall j\in J_i \qquad\qquad (8)$$

$$-z_{ij} + h'_i z'_{ij} \ge 0 \qquad\qquad \forall i\in B,\ \forall j\in J'_i \qquad\qquad (9)$$

$$y'_{ij} + z'_{ij} \le 1 \qquad\qquad \forall i\in C,\ \forall j\in (J_i\cup J'_i) \qquad (10)$$

$$x_j \ge 0 \qquad\qquad\qquad \forall j\in J \qquad\qquad\qquad (11)$$

$$y_{ij}=\text{integer and } y'_{ij}=\text{binary} \qquad \forall i\in A,\ \forall j\in J_i \qquad\qquad (12)$$

$$z_{ij}=\text{integer and } z'_{ij}=\text{binary} \qquad \forall i\in B,\ \forall j\in J'_i \qquad\qquad (13)$$

The model is adapted from the paper, "The Siting of Emergency Service Facilities with Workload Capacities and Backup Service" (Pirkul and Schilling, 1988).

The first objective function (1.1) minimizes the number of aircraft. The problem is solved with constraints (3) through (13). Constraint (2) is excluded from the first optimization problem simply because constraint (2) fixes the total number of aircraft to be located (which is the optimum objective function value of the first problem).

The second objective function (1.2) minimizes the sum of the travel distances between the areas of interest with primary coverage requirement and assigned candidate points for the primary coverage, plus the sum of the distance between the areas of interest with backup coverage requirement and assigned backup sites. The distances are weighted by the number of aircraft. This problem is solved with constraints (2) through (14).

Constraint (2) allows only P aircraft in the solution; this value is the minimum number of aircraft to cover the area. Constraint (3) is the additional constraints defined by the user. These constraints require that some minimum, maximum or exact number of aircraft be located at specified airbases.

Constraint (4) ensures the required number of aircraft are located to satisfy the primary coverage of the overall network. Constraint (5) ensures the required number of aircraft are located to satisfy backup coverage requirements.

An aircraft located at site j could be serving primary and/or backup coverage of different demand points. Therefore, the number of aircraft located at site j must be at least as many as the maximum number of aircraft required at site j to satisfy the demand within

the coverage distance of site *j*. Constraint (6) enforces this for primary coverage and constraint (7) enforces this for backup coverage.

Constraints (8) and (9) assign values for implication variables. If y_{ij} or z_{ij} is assigned a number, then $y_{ij}^{'}$ or $z_{ij}^{'}$, respectively, is assigned 1; otherwise, they are set to zero. Constraint (10) assures that the set of aircraft assigned for the primary coverage cannot be assigned to the same demand point's backup coverage. Therefore, it also ensures that no primary and backup aircraft for any point are located at the same base. Constraints (11), (12) and (13) are non-negativity and integrality restrictions on variables; y_{ij}, $y_{ij}^{'}$, z_{ij} and $z_{ij}^{'}$ exist for those combinations when the demand point is within the coverage distance of the candidate point. They do not include every possible combination of the demand points and the candidate points in the model.

Most literature about this problem deals with facility location; the formulation and solution techniques usually do not include vehicles located at the facilities. This research's model is for location of emergency service vehicles with backup coverage requirements.

Backup coverage is required for facilities that are prone to disruptions such as airbases. The model is capable of handling backup coverage as well as primary coverage as a requirement. The model does not allow the aircraft that satisfy the primary coverage of an area to be assigned to the backup coverage of the same area. A set of implication variables is included in the formulation for this purpose. A different set of aircraft from a different base must be assigned the backup coverage; however, the aircraft assigned the primary coverage of an area can be assigned the backup coverage of a different area.

The model developed in this research determines not only on the facility locations but also the number of vehicles required at the facility. Unlike previously conducted research, for this problem more than one service vehicle can be positioned at a candidate point and the demand points may require more than one unit of service. Therefore, coverage is satisfied when the required number of service vehicles are placed at the candidate points that cover each demand point. Additionally, the coverage range of each candidate point may be different because each aircraft type has a different coverage range.

The location of the facilities usually depends on historical demand data from the region they serve; however, the demand size and location are dynamic in nature and are changing with time. As a result, it is occasionally necessary to re-evaluate the number of vehicles at the facilities. The proposed model can also be used in the reconsideration process. The model can determine the number of service vehicles at the existing facilities without adding or changing the location of any emergency facility.

3.9 Pseudocode

The pseudocode for the tool is presented below:

1. GET input parameters from the user:

Alert states, aircraft, bases, compatibility chart, additional constraints, regions and requirements

2. CALCULATE the demand points' coordinates (Aggregation)

3. CALCULATE the distances between demand points and candidate points

4. CALCULATE coverage of each site and the demand points within range

5. IF NOT all the demand can be satisfied

     REPORT the demand points that cannot be satisfied

     EXIT

  END IF

10. CALCULATE the objective function, the constraints matrix and the RHS

11. OUTPUT the model as an MPS file

3.10 Summary

Chapter 3 presented detailed analyses of the problem and the methodology of the solution is introduced. The tools that are available to generate a solution were reviewed and a tool was developed in order to efficiently address the problem. A tool, ARK, was developed in order to realize the objectives of the research. Due to the size of the code of the tool (131 pages), it is presented in Appendix B. The user's guide for the tool is presented in Chapter 4 and the validation of the tool is done in the Chapter 5.

IV. ARK Tool

4.1 Overview

The Turkish Air Force locates alert aircraft in order to protect Turkish airspace. Different regions of the airspace can have different alert states. The alert state is defined in terms of response time and number of aircraft to respond. The research question associated with this problem is:

What is the optimum location of the alert aircraft such that the number of aircraft is minimized and the alert network objective is met?

The alert states and the definition of regions may change in time as well as the aircraft inventory and airbase availability.

ARK (*Alarm Reaksiyon Konuşlandır* in Turkish / *Locate Alert Aircraft* in English) is a tool designed for the Turkish Air Force to locate the alert aircraft at Turkish airbases. It is flexible in adding, changing or deleting alert states, regions, aircraft and airbases. It generates a location model file according to user specified requirements.

ARK is developed in Visual Basic for Applications in Microsoft Excel. The user is encouraged to use Microsoft Office 2003 or earlier versions with the tool for best results.

The main user interference of ARK is shown in Figure 3. The *Wizard* button allows the user to generate a solution. The pseudocode given in the previous chapter is executed by the Wizard. The *Custom Solution* button is a tool for determining the coverage for a set of airbase and aircraft combinations given by the user. The ARK tool generates reports in order to present the solutions. The reports include a coverage map of

coverage and some basic statistics. The last generated report is saved; the user can view, modify and print the last report by the *View and Modify Last Report* button.

Figure 3 – Main Screen of ARK

The *Help & About* button shows information about the tool and the contact information. Additionally the history of the problem, methods of solution and user's guide are available at the help screen. The *Save* button saves the current file. The tool requires a confirmation before saving. The *Reset* button clears all tables and settings in the tool. This button must be used when the user encounters a problem when generating the model or when the tool fails. All data is cleared; the required input information for the aircraft, airbase, etc must be re-entered prior to generating the model. It is strongly recommended that the user saves the file before generating any model. The tool requires two confirmations to ensure the user fully understand the consequences of resetting the tool. The *Minimize* and *Exit* buttons perform their equivalent functions in Windows.

4.2 Custom Solution

Custom solution is a tool for determining the coverage for a set of airbase and aircraft combinations; its first window is shown in Figure 4. For example, if the user wants to see the 15-minute-coverage for the aircraft and airbase combinations in Table 1, he/she will need to use the Custom Solution tool.

Table 1 – Sample Aircraft & Airbase Combination

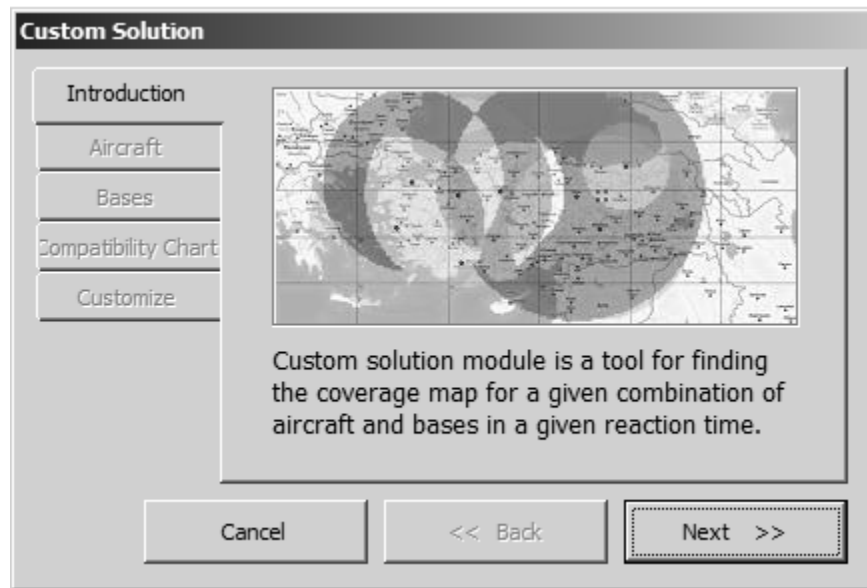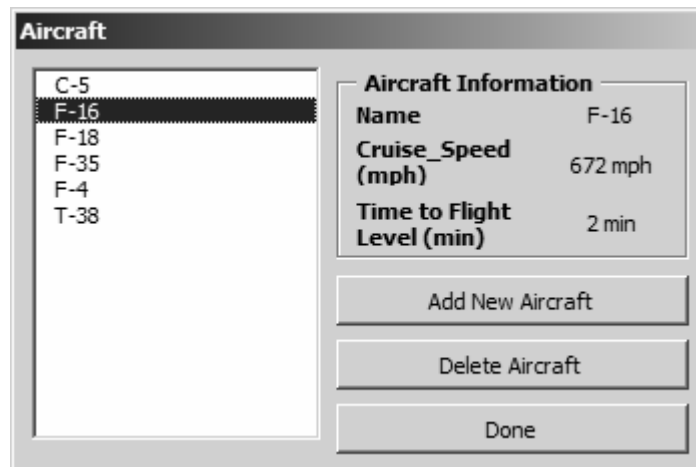| Aircraft	Airbase
2xF-16	Ankara
2xF-35	Bandırma
2xF-4	Malatya

Figure 4 – Custom Solution Screen

Figure 5 – Aircraft Screen

The aircraft, bases, compatibility chart and the reaction time are required in order to generate a coverage report. The second step of the Custom Solution is the aircraft step (Figure 5). The user can add, delete or review the aircraft in this step. New aircraft can be added by clicking the Add New Aircraft button (Figure 6).

Figure 6 – Add New Aircraft

The aircraft name must be a text string; it can contain numbers, but the first letter of the name cannot be a number. The first 4 letters of the aircraft must be unique; the user must be able to differentiate aircraft using the first 4 letters.

The cruise speed is the speed of the aircraft in nautical miles per hour when it reaches its interception altitude and flies at this speed until it intercepts the intruder. Mach speed changes with altitude. MACH_Calc is a tool for aiding the user to convert mach speed into NM for a specific altitude (Figure 7). For this speed, the threat's anticipated altitude should be used.
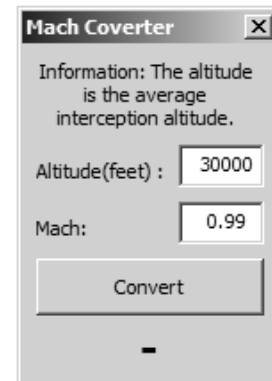
Figure 7 – MACH_Calc

The time to flight level is the time in minutes that is required for the aircraft to climb to its interception altitude. The beginning of this time depends on the user. If the user assumes that there is no difference between the performances of aircraft of the same type from different airbases, he\she can enter the required time from the takeoff to climb interception altitude. If there is assumed to be a difference between airbases and data is available for different take off times, then an aircraft can be modeled as several different aircraft with the same airspeed but different 'time to flight level' values. For example, assume that the F-16 aircraft from X airbase requires an average of 7 minutes to take off after the scramble order is given; the same F-16 may require 10 minutes at airbase Y. This difference could be due to several different local conditions such as taxi time or training levels. These differences can be modeled in the tool by entering two different F-16 aircraft with different 'time to flight level' values. If an F-16 aircraft reaches its interception altitude in 2 minutes from takeoff time, then the 'F16X' aircraft 'time to flight level' value is 7+2=9 and the same value for 'F16Y' is 10+2=12 minutes. This would indicate the difference between airbases with the same type of aircraft. As stated before, this method is not required, but if the user has data available for the takeoff times

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of an aircraft type from different airbases, this would more adequately encapsulate the scenario.

After adding, deleting or reviewing the aircraft, next step in the custom solution is to add, delete or review the airbases. The user interface for performing this step is presented in Figure 8.

Figure 8 – Airbases Screen

The airbase name and the coordinates are two required fields in order to add a new airbase form. The airbases are added by selecting a location on the map tool (Figure 9). A red square appears at the base location after location selection; the location's coordinates are shown in the box below the map. The *exact coordinate* is not required for the airbases. Therefore, if the coordinate is different from the real coordinate to the 3rd significant digit, this does not constitute a problem in terms of solution accuracy as the bases have sufficient distance from each other. When choosing a name for the airbase, the user must select the names such that the airbases can be differentiated by the first 3 letters.
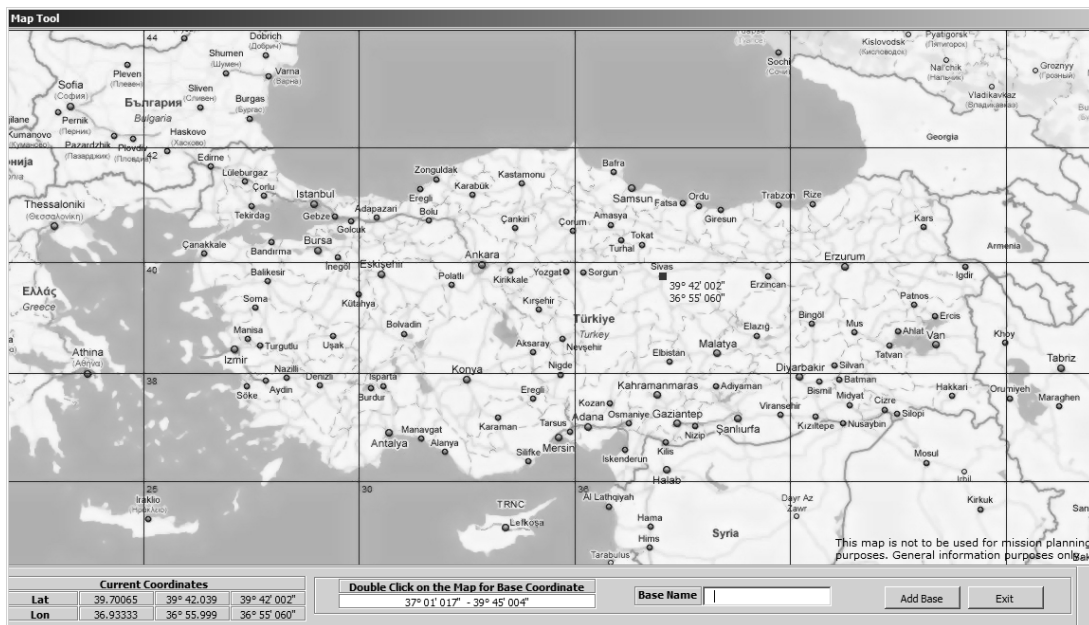
Figure 9 – Map Tool

The Next step in using ARK is the compatibility table (Figure 10). This table is used to indicate the compatible aircraft and airbase combinations. All the previously entered aircraft and airbases are in the table.
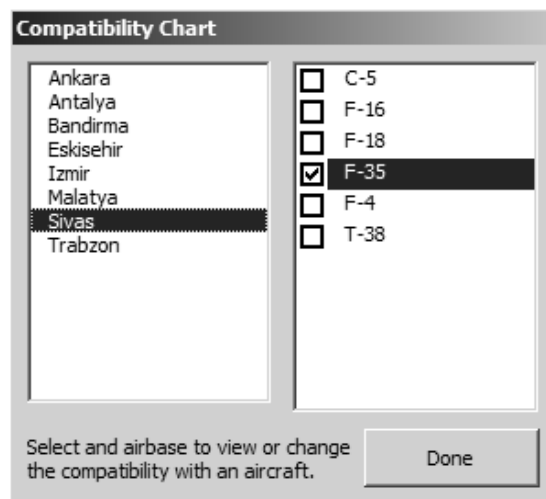
Figure 10 – Compatibility Chart

The last step of the custom solution tool is *Customize*. The user interface for this portion of ARK is presented in Figure 11. At this step, the user adds/deletes aircraft to/from bases. Adding an aircraft to a base implies locating the aircraft at that base. An aircraft may be compatible with an airbase but as long as it is not added to this list, it is not included in the coverage report. When adding a combination of aircraft and airbase, the tool checks if they are compatible.
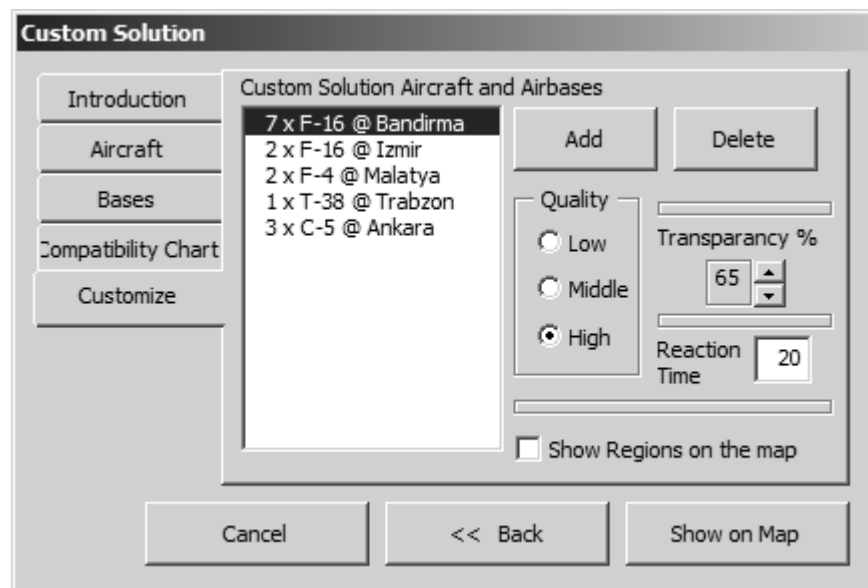
Figure 11 – Customize Solution

The coverage is calculated according to the reaction time entered in this step. The coverage map in the report is the coverage in the reaction time period. The quality of the report is in terms of the resolution of the map. More computation time is necessary if higher resolution is required.

The user can also see the regions that he\she added in the Wizard. If the "Show Regions on the Map" checkbox is checked, the regions are shown on the map. Figure 12

is a sample report. In the report, the regions are colored according to the number of

aircraft covering the region; the legend for this is shown below the map. It is important to

note that the colors indicating the number of aircraft and the colors for the alert states are

different and should not be confused.

The alert aircraft are located at red highlighted airbases. The first section of the

report is the user input data. The percentage of the covered region with respect to total

visible region in the map is then shown. The second section is the airbase and aircraft

combinations' coverage percentages with respect to total covered region. They might not

sum up to 100% because some regions may be covered by multiple aircraft. The last

portion of the report is a listing of the coverage percent versus the number of aircraft. The

colors on the map represent the number of aircraft; the legend for this is below the map.
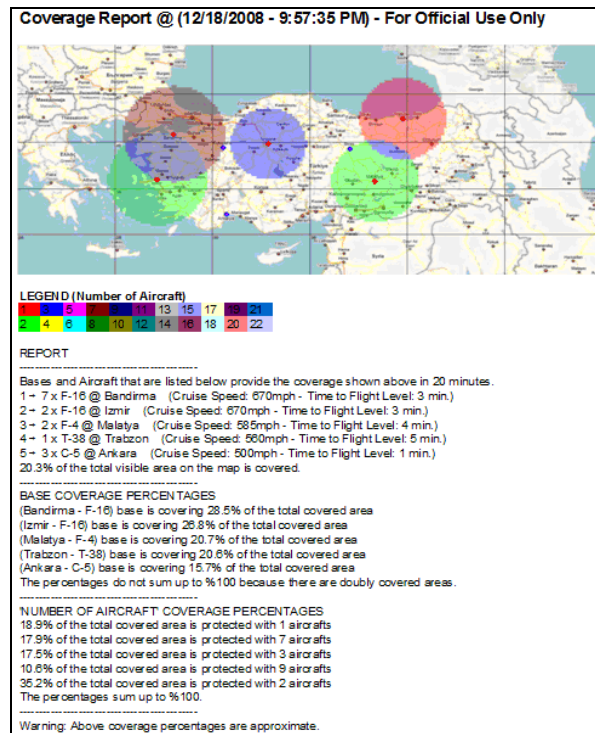
Figure 12 – A Sample Report

4.3 Wizard

The wizard section of ARK allows the user to generate a mathematical model. The solution of the model is the optimum location for the alert aircraft. The main screen of the wizard is shown in Figure 13.
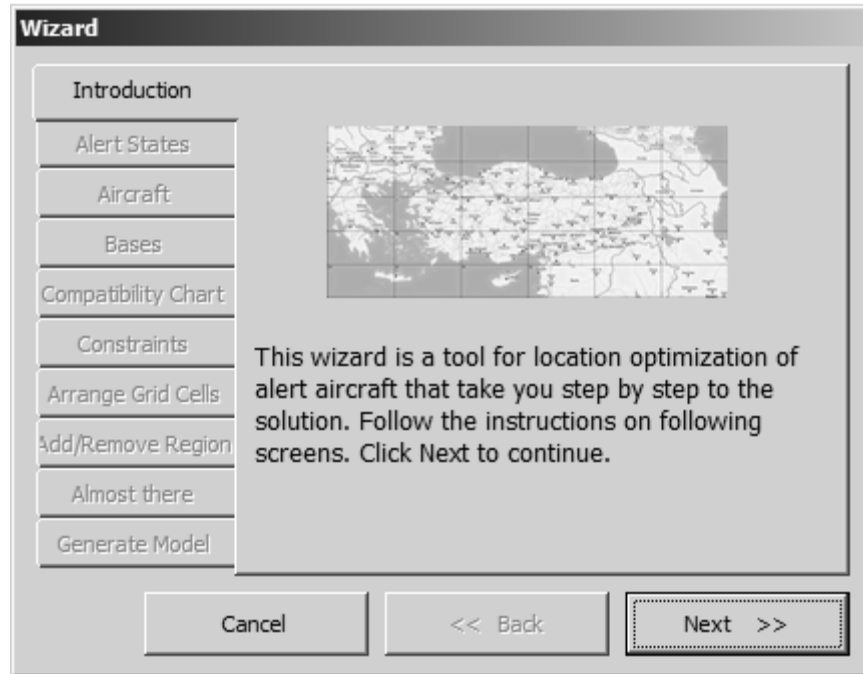
Figure 13 – Wizard Screen

The first screen is the introduction. In second step, the user defines up to 10 different alert states. The user interface for this step is shown in Figure 14. The alert states are defined in terms of response time and response aircraft. For the example in Figure 14, the alert state 1 requires 7 aircraft in 15 minutes. Thus, if the user selects any region alert state as red (alert state 1), that region must be within 15 minutes reaction range of 7 aircraft or more.
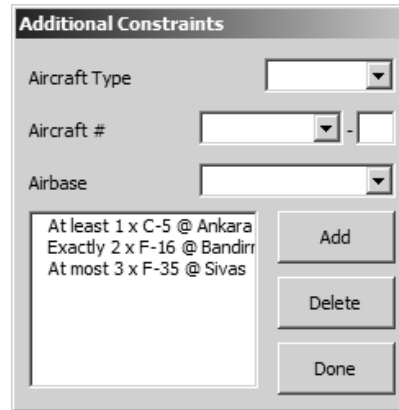
Figure 14 – Alert States

The third, fourth and fifth steps are the available aircraft and airbases and the compatibility chart, respectively. These are the same as the custom solution menu. The sixth step involves defining the additional constraints. The user interface for this step is presented in Figure 15. If the user prefers to include additional constraints in the model, they can be entered at this step. As seen in Figure 15, there are 3 types of constraints: "At Least", "Exactly" and "At most". Therefore, the user can enter upper and lower bounds

on aircraft at some airbases or include a set of aircraft in the solution that is already

available.

Figure 15 – Additional Constraints

The user interface for the *Add\Remove Region* step is shown in Figure 16.

Figure 16 – Add/Remove Region

In this step, the form in Figure 16 is displayed and the background sheet is the map. In this step, the user adds or removes regions to be covered. The alert states that were entered in the second step are shown for information on this form.

There are two types of coverage: primary and backup. For example, if the primary coverage is red for a region, then that region must be reached in 15 minutes with at least 7 aircraft. The backup coverage, on the other hand, can be different from the primary coverage's alert state. This is to backup the primary coverage in case of a base disruption. A base could be disrupted for several reasons such as weather, attack, etc. The user might desire to backup important regions with an alternate coverage. A different set of aircraft are assigned to cover the backup coverage; these aircraft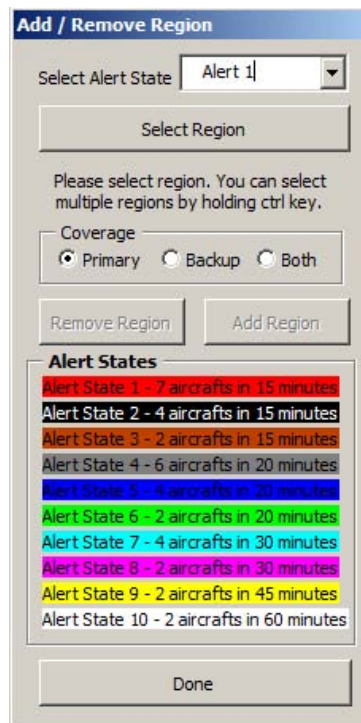 are located at a different base than the base providing primary coverage. The aircraft that are located as backup coverage for a region can be the primary coverage for another region.

In terms of solution, there is no difference between primary coverage and backup coverage. If the user desires to include a backup coverage to a region where no primary coverage exists, the tool will generate a solution with only this type of coverage. In reality, though, the user may have neglected to include the primary coverage; therefore, a warning message is displayed, if this occurs.

The primary coverage is displayed as a circle on the map; its outer line is colored as the alert state color. It is located at the center of the square cell in the region. The backup coverage color is the fill color of the same circle.

When adding a region, the user should select the alert state first. Next, the region receiving this alert state is selected by dragging the mouse over the map. After selecting

the OK button, the user is returned to the form. Finally, the user selects the *Add Region* button and the region is displayed on the map.

One important thing to note is that the circles are added to Excel as shapes. Thus, when selecting another region, the user may inadvertently relocate those shapes. Fortunately, the tool will automatically correct this error. It can be difficult to select a region that is already selected (for example, in order to add backup coverage for a region that already has primary coverage). Thus, the user is cautioned to be patient and careful on this step. In case of a failure, it is recommended to return to the return back to wizard and reattempt the process.

The next step is a review. Before proceeding to the last step, preprocessing is accomplished. This is to verify that the user-defined region is coverable with the given aircraft and airbase combinations. If there is a region that cannot be covered, a report is given which shows the regions that are not coverable.

A sample case is shown in Figure 17. All 4 types of uncovered regions that are mentioned in preprocessing section of the previous chapter are shown in this example. Even if the tool locates the aircraft to every airbase, these highlighted demand points cannot be covered.

Coverage Report @ (12/11/2008 - 12:30:48 AM) - For Official Use Only

REPORT
_____

Some area defined by the user can not be covered by no means.
-   The orange highlight is if the backup demand can not be covered.
-   The black highlight is if the primary demand can not be covered.
-   The red colored NO SYMBOL highlight is if both the backup and primary demand can not be covered.
-   The blue highlight is if both backup and primary coverage is required but only one can be covered.

All these are violations for your solution and the problem can not be solved. Therefore you can either redefine the problem or remove these uncoverable demand areas.

Figure 17 – A sample for No Coverage Report

After reviewing and closing this report, the user is asked to remove the regions that cannot be covered. When removing, if both primary and backup coverage is required and only one is coverable, backup coverage is removed. Therefore, the user must review what has been removed after confirming removal.

The last step is the model generation. The user interface for this section is shown in Figure 18. The models are generated as a math programming system file that common optimization software can read and solve (LINGO, Excel Solver, CPLEX and lp_solve are among those software). The user can save this file to a local storage media.

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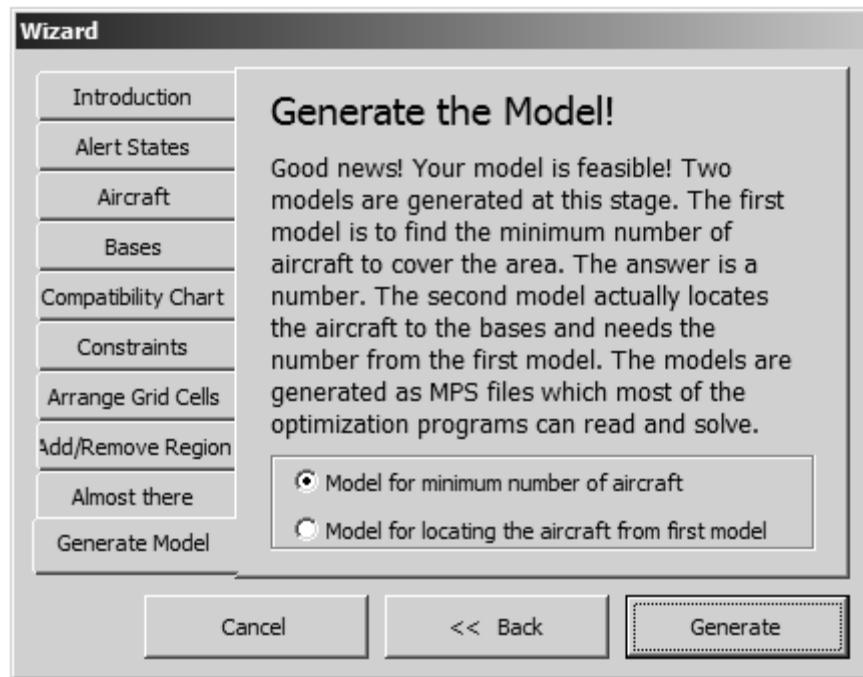
Figure 18 – Model Generation

The first solution is for to the minimum number of required aircraft. This is the set covering location problem. The objective function value of this model is the minimum number of aircraft to cover the user-defined regions.

The user can load the mps file in optimization software and solve it. When reading the mps file, the optimization software translates the mps file into its own language and structure. During this translation, some naming errors could occur; however, the optimization software solves typically corrects these issues. For instance a message from LINGO is shown in Figure 19. LINGO patches the names to make them compatible with its own standards.
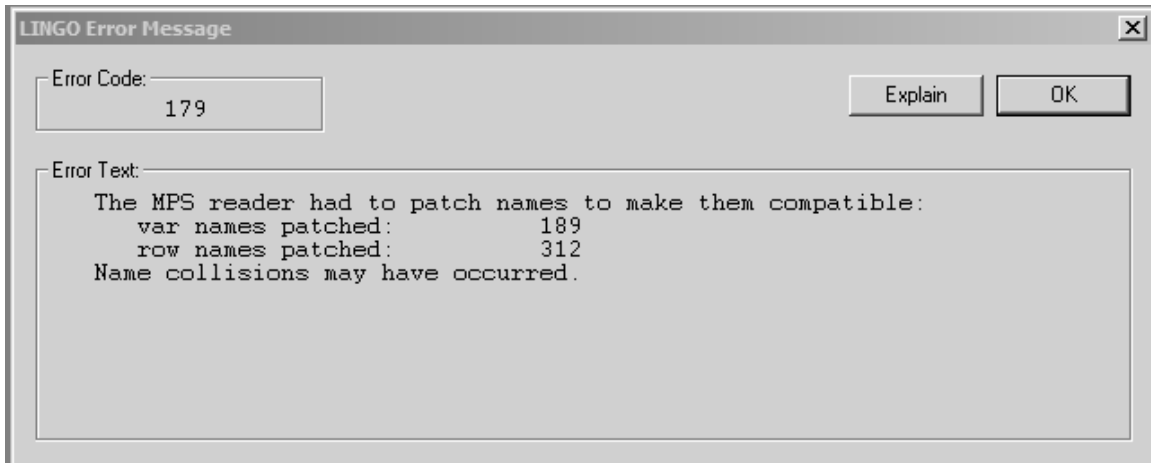
Figure 19 – LINGO Translation Message
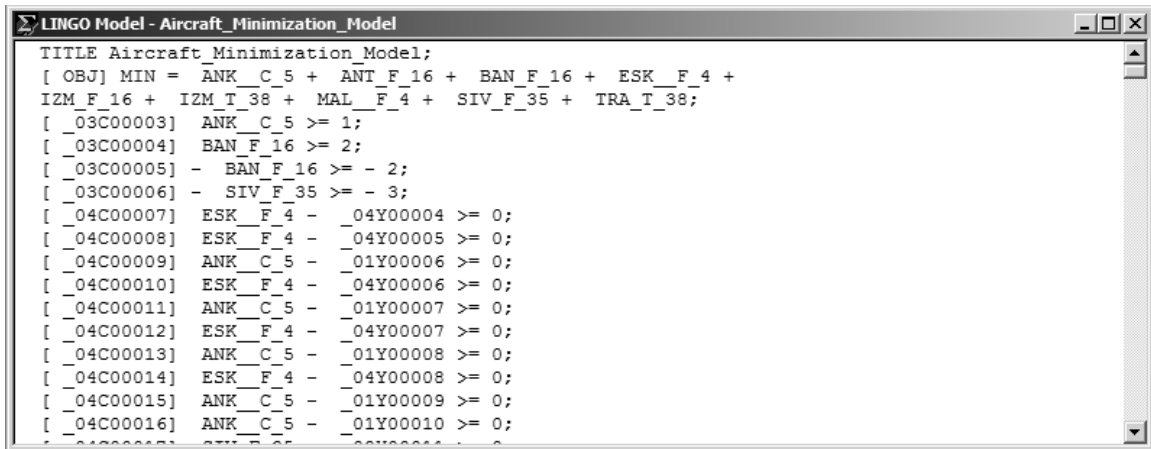
Figure 20 – Model in LINGO

Figure 20 is a sample model in LINGO software. After solving the first portion of the problem, the minimum number of aircraft to satisfy the alert regions is known. The second step is to create the Location Model which determines the actual locations of the alert aircraft. *Without* changing any alert state/aircraft/airbase/compatibility chart or regions, the location model is created. The user must run the wizard again and click the "next" button until the last screen (Figure 18) is displayed. At this screen, the second

option (model for locating aircraft from the first model) must be selected. The tool then

asks for the number from the first solution (Figure 21).
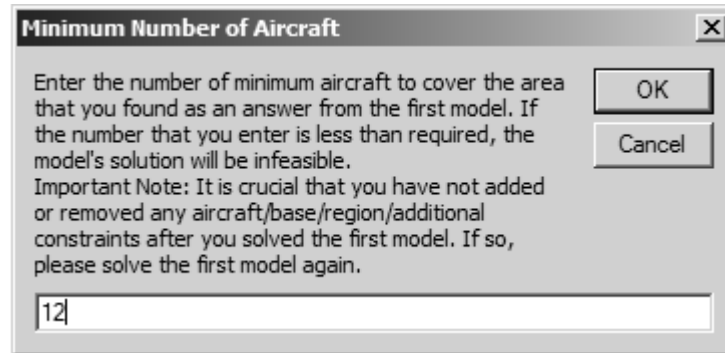
Figure 21 – Location Model Information

After entering this value, the location model is generated and saved as an mps file.

The solution of the model is obtained from the optimization software. At this step, the

user should know which variables are of interest. The variables that will give the answer

are of the "BBB_AAAA" format where BBB is the first 3 letters of the airbase and

AAAA is the aircraft name's first 4 letters. If they are less then 3 or 4 respectively, then

an underscore character is inserted.

The initials of all the other variables are numbers; these are not important when

searching for the optimum location of the alert aircraft in the solution of the model.

Further information on all the variables is presented in next section.

When the user obtains the result from the location model, he/she can add the

solution to the custom solution portion of the ARK tool. On the last screen (Figure 18),

he/she can check the "Show Regions on the Map". Then the coverage map is displayed

with the user-defined regions in the background.

4.4 How to Read the Model Results

The objective function value is the only relevant portion of the solution of the first model. For the second (location) model, the objective function value is not of primary importance. In order to determine the optimum location for the aircraft, the values of the variables in the solution must be observed.

The model is presented in chapter 3 of the thesis. There are six types of names in the mps file. Five of the names are variable name types and one is the constraint name. In order to determine the optimum location of the alert aircraft, only one type of variables is relevant. In this section, all variable and constraint names will be described.

The first name is the constraint names. The constraints name format is: **##C#####** where # stands for a number from 0 to 9. The first 2 digits are the constraint type number. The constraint type numbers are across each constraint in the formulation in chapter 3 of the thesis. The letter C stands for constraint and the following 5 digit number is the constraint number starting from 1 until the end of the constraints. The second name was mentioned in previous section. The format of these names is: BBB_AAAA where BBB is the first 3 letters of the base and the AAAA is the first 4 letters of the aircraft. If the name is less than 3 or 4 letters respectively, an underscore is replaced instead of missing characters. The third name is the Y_{ij} variable in the model in chapter 3 of the thesis. Its format is ##Y##### where the first two digits stand for the i and the last five digits stand for the j value in Y_{ij}. In the same way, the fourth name, ##Z#####, is the Z_{ij}. The fifth name, ##B#####, is the $Y^{'}_{ij}$ and the sixth name, ##A#####, is the $Z^{'}_{ij}$.

V. Analysis and Results

5.1 Introduction

A tool is developed for location optimization of the alert aircraft that can adapt to changes in threat anticipation while meeting the objectives of the alert network. The tool is flexible in adding, changing or deleting alert states, regions, aircraft and airbases.

This chapter deals with the validation of the tool. Three sample problems are solved in this chapter for demonstration purposes. All scenarios are fictitious; they do not reflect the reality of threat perception in Turkey. The scenarios are chosen such that all the capabilities of the tool are shown in detail. The method for solving the scenarios can be duplicated in order to carry out similar analysis on real-world problems.

The first scenario is the simplest case. There is only one region and the alert state for the whole region is the same. The second and third scenarios build upon the first. In these scenarios, the number of regions is increased and each region's alert state is different.

All analyses in this chapter were accomplished on a computer with an Intel Core (2) Duo T7300 @ 2Ghz processor, 2GB RAM and Windows Vista Home Premium operating system.

5.2 Data

Due to security classification, real-world data is not used. The data presented below is generic. The airbases and the compatibility chart are in Table 2. The airbase information is from the Internet (Wikipedia, 2008d). The first three columns (from the

left) are the names of the airbases in 3 different formats; the coordinate of the airbase is in column 4. The remaining columns detail available aircraft. The value after each aircraft's name is the elapsed time from receipt of the scramble order to the aircraft achieving the interception flight altitude. An 'X' in the table indicates compatibility between the base and the aircraft.

Table 2 – The Airbase Information, and the Compatibility Chart

Name	Name in the Tool	ICAO	Coordinate	F-16 11min	F-16 13min	F-16 15min	F-4 12min	F-4 14min	F-4 15min	F-5 14min
Afyon	AFY	LTAH	38°43′N 30°35′E			X				
Akhisar	AKH	LTBT	38°48′N 27°50′E			X			X	
Akıncı	AKI	LTAE	40°04′N 32°33′E	X						
Aydın	AYD	LTBD	37°48′N 27°53′E					X		
Balıkesir	BAL	LTBF	39°37′N 27°55′E	X						
Bandırma	BAN	LTBG	40°19′N 27°59′E	X						
Batman	BAT	LTCJ	37°56′N 41°07′E		X					
Bursa	BUR	LTBR	40°15′N 29°33′E						X	
Çanakkale	CAN	LTBH	40°08′N 26°25′E						X	
Çardak	CAR	LTAY	37°47′N 29°42′E			X				
Çiğli	CIG	LTBL	38°30′N 27°01′E		X			X		X
Çorlu	COR	LTBU	41°08′N 27°55′E			X				
Dalaman	DAL	LTBS	36°42′N 28°47′E			X			X	
Diyarbakır	DIY	LTCC	37°53′N 40°12′E	X						
Elazığ	ELA	LTCA	38°36′N 39°17′E						X	
Erzincan	ER1	LTCD	39°42′N 39°31′E			X				

Name	Name in the Tool	ICAO	Coordinate	F-16 11min	F-16 13min	F-16 15min	F-4 12min	F-4 14min	F-4 15min	F-5 14min
			Table 2 – continued							
Erzurum	ER2	LTCE	39°57′N 41°10′E	X						
Eskişehir	ESK	LTBI	39°47′N 30°35′E				X			
İncirlik	INC	LTAG	36°57′N 35°17′E	X			X			
Kayseri	KAY	LTAM	38°24′N 35°19′E		X					
Kocaeli	KOC	LTBQ	40°44′N 30°05′E			X				
Konya	KON	LTAN	37°58′N 32°33′E		X			X		X
Kütahya	KUT	LTBN	39°26′N 30°01′E			X				
Malatya	MAL	LTAT	38°26′N 38°05′E				X			
Merzifon	MER	LTAP	40°50′N 35°31′E	X						
Muş	MUS	LTCK	38°44′N 41°39′E	X						
Sivrihisar	SIV	LTAV	39°27′N 31°22′E			X				
Uşak	USA	LTBO	38°40′N 29°28′E						X	
Yalova	YAL	LTBP	40°41′N 29°22′E						X	

The aircraft specifications are in Table 3. The names of the airbases and the aircraft are modified in order to meet the tool's naming standards. The third column is the cruise speed in nautical miles per hour. The fourth column is the time to interception altitude. The difference between airbases' takeoff time performances is represented by creating different aircraft. If the user does not want to differentiate performance between the same aircraft types at different bases, the user can simply enter only one aircraft for each aircraft type; the 'time to flight level' value is then the time from takeoff until it

climbs to the interception altitude. There are a total of 29 airbases, 7 aircraft types and 36

possible compatible combinations. The alert states are shown in Table 4.

Table 3 – The Aircraft Information

Aircraft	Name in the Tool	Cruise Speed(NM)	Time to Int. Altitude (Min)
F-16	F161	448	11
F-16	F162	448	13
F-16	F163	448	15
F-4	F41	417	12
F-4	F42	417	14
F-4	F43	417	15
F-5	F5	386	14

Table 4 – Alert States

Number	Color	Response Time (Min)	Response Aircraft Requirement
1	Red	30	6
2	Black	30	4
3	Brown	30	2
4	Orange	35	6
5	Blue	35	4
6	Green	35	2
7	Turquoise	40	4
8	Pink	40	2
9	Yellow	50	2
10	White	60	2

The additional constraints for these scenarios are shown in Table 5. The data presented in this section is the same for the three scenarios.

Table 5 – Additional Constraints for First Scenario

Number	Constraint Type	Aircraft number	Aircraft type	Base
1	At least	2	F161	Bandirma
2	Exactly	2	F163	Afyon
3	At Most	2	F42	Aydin
4	At Most	4	F162	Batman
5	At Most	2	F43	Burdur
6	At Most	2	F163	Cardak

5.3 Coverage Analysis

The ARK custom solution tool produces several statistics related to coverage. Using the tool, the maximum coverable region is calculated for different reaction times (Table 6). It is assumed that all aircraft shown in Table 2 are located at each compatible airbase. The first column from the left in Table 6 is the reaction time; the second column is the corresponding alert state. Some alert states have the same reaction time but a different number of responding aircraft. Therefore, there are more than one alert state in some rows. The third column is the total covered region (as a percentage) with respect to the total region on the map. The fourth column is the region that is covered by only one airbase, and the last column is the region covered by at least two airbases. In order to provide both primary and backup coverage, at least two airbases are required within range of the demand point.

Table 6 – Coverage by Reaction Time

Reaction Time (Minutes)	Corresponding Alert state	Total Covered Region * (%)	Region Covered by 1 base* (%)	Region Covered by at least 2 bases* (%)
20	N/A	17.1	10.7	6.4
25	N/A	30.8	11.3	19.5
30	Red, Black, Brown	41.1	8.7	32.4
35	Orange, Blue, Green	51.8	8.6	43.2
40	Turquoise, Pink	62.6	9.1	53.5
45	N/A	71.4	7.4	64
50	Yellow	77.9	5	72.9
55	N/A	83.8	4.4	79.4
60	White	88.9	3.3	85.6

* Percentages are with respect to total visible region on the map
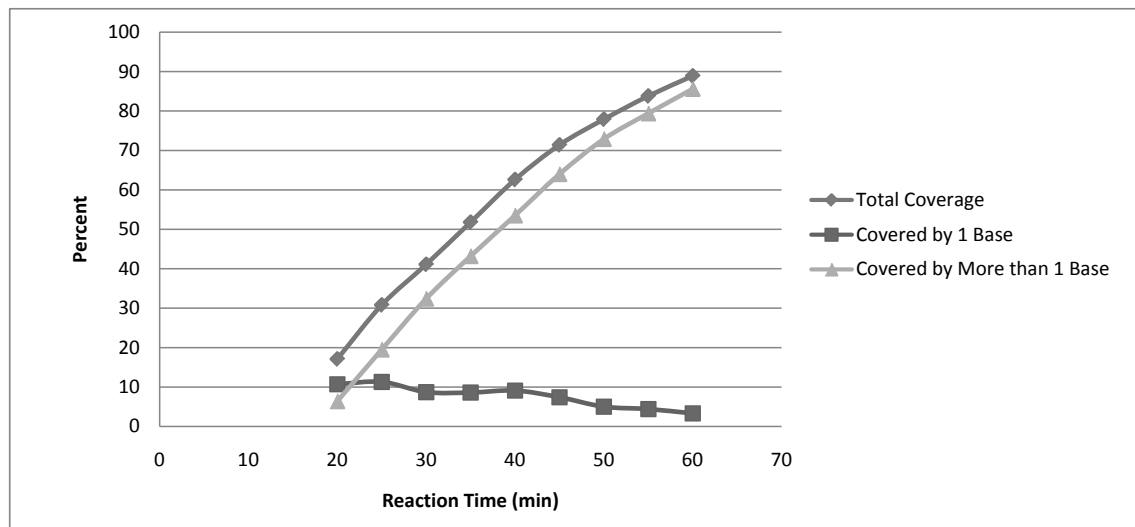
Figure 22 – Coverage Percentage with respect to Visible Area on the Map

As seen in Figure 22, the area that is covered by at least 2 airbases rapidly

increase after 20-minute reaction time. But for 20-minute reaction time, only 6.4 % of the

region can receive backup coverage.

If the backup coverage cannot be satisfied for a region, relaxing the reaction time would provide more airbases to cover the region and therefore the backup coverage could be satisfied.

5.4 Scenario 1: One Region – One Alert State

In the first scenario, there is one region with a yellow alert state. No backup coverage is required. The region is shown in Figure 23.
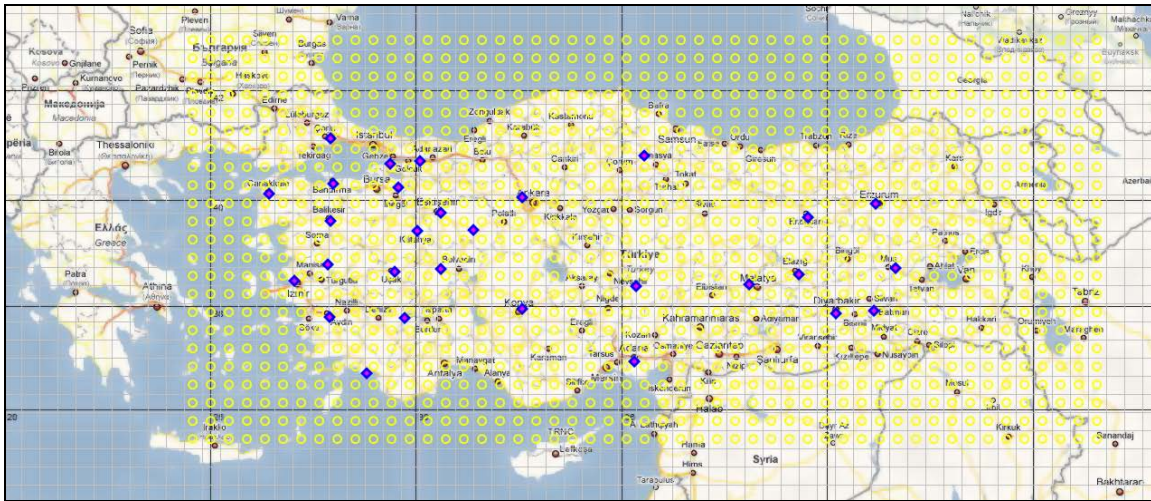
Figure 23 – Coverage Requirement for First Scenario

The wizard of the ARK tool is run. The preprocessing is carried out on the last step of the wizard. The tool produced a report showing the regions that are not able to be covered with the current configuration of aircraft and airbases. The uncovered regions are the black highlighted circles in Figure 24.
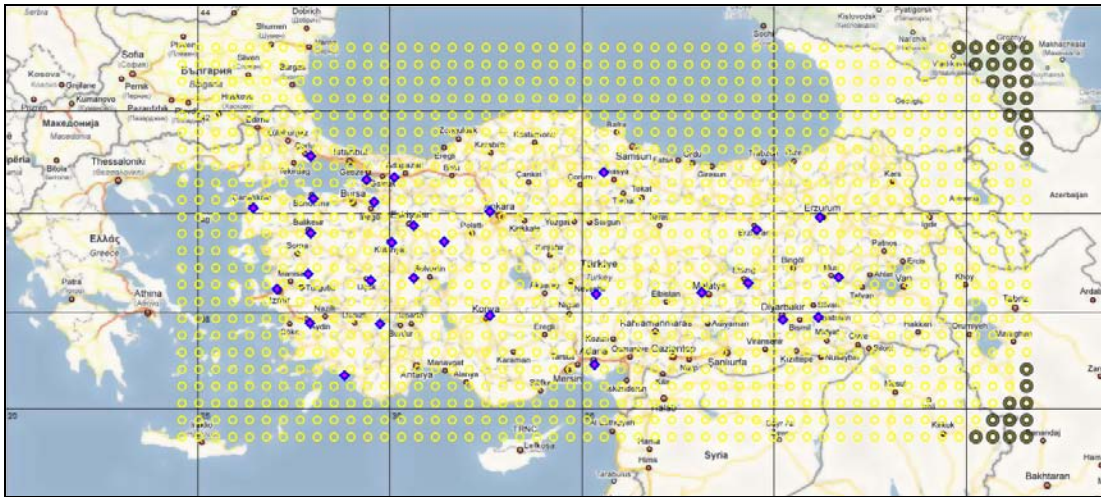
Figure 24 – Uncoverable Region for First Scenario

The user must decide how to proceed. If the areas in which no coverage does not constitute a deficiency in national air defense, these regions can be removed. This is done automatically by the tool. After removing the region that cannot be covered, the SLCP model is generated (Figure 25). The solution required 7 minutes and 16 seconds to generate. The MPS file is presented in Appendix C.
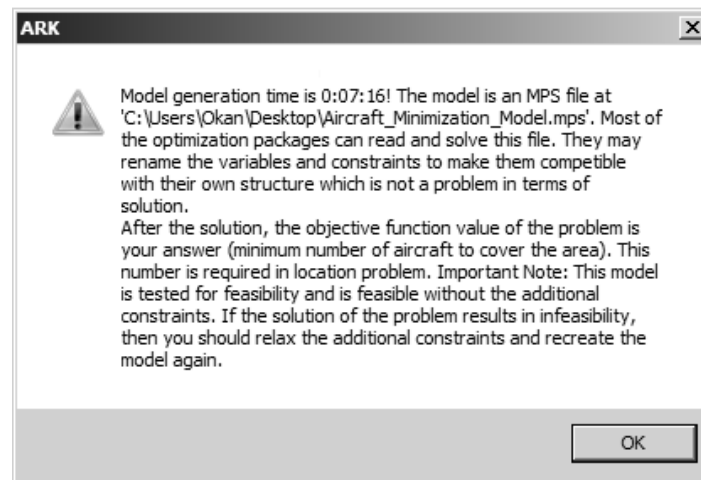
Figure 25 – SCLP Model Generation Message for First Scenario

The model was solved using LINGO optimization software. The LINGO model is in Appendix D. The model has 25,242 variables, 25,416 of which are integer. The total number of constraints is 26,619. LINGO solved the model in 2 seconds. It is relatively quick due to the restrictive nature of the problem. The objective function value of the first model is 14, which indicates that 14 aircraft are needed to cover the entire region for the given alert state requirements. The solution report of the model is in Appendix E. The location model is generated without changing any settings or data from the first model (Figure 26).
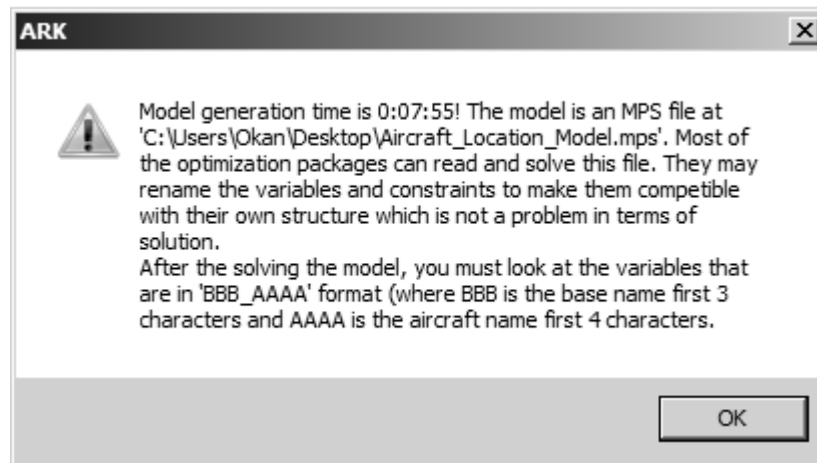
Figure 26 – Location Model Generation Message for First Scenario

The location model is generated in 7 minutes and 55 seconds and it has 25,242 variables, 25,416 of which are integer. The total number of constraints is 26,621. The MPS file is in Appendix F and the LINGO file is in Appendix G. LINGO solved the model in 56 seconds. The solution is presented in Table 7. The solution report is in Appendix H. There are 14 aircraft located at 7 different airbases in the solution.

Table 7 – The Result for First Scenario

Base	Aircraft	Base	Aircraft	Base	Aircraft	Base	Aircraft
Afyon	2xF163	Dalaman	2xF163	Incirlik	2xF161	Mus	2xF161
Bandirma	2xF161	Erzurum	2xF161	Merzifon	2xF161		

The yellow alert level requires reaction in 50 minutes. Therefore, a 50-minute coverage report is generated using *Custom Solution* tool (Figure 27). The shaded region in the figure is covered. The red highlighted airbases are in the solution set. The alert aircraft are reasonably spread throughout Turkey. Although the aircraft are mostly located on the outer border of the country (to cover the outer parts of the region), the Anatolia hinterland is also covered.

It should be noted that additional constraints required location of exactly 2 aircraft at Afyon Airbase in central-western Turkey. When this additional constraint is removed, it is observed that the remaining 12 aircraft can also cover the user-defined region.

As shown in the figure, the entire user-defined region is covered and a total of 74.3 % of the area shown on the map is covered; 36.2 % of the covered area is protected by only 2 aircraft. The remaining, 63.8 % of the covered region is covered by 4 or more aircraft. This implies that the area covered by 4 or more aircraft could be provided backup coverage, if requested. Other exclusive statistics such as the aircraft information or base coverage percentages are presented to the user in the report.
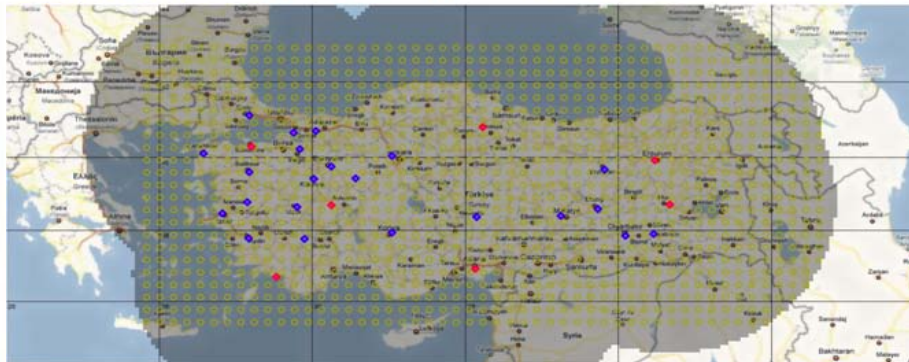
REPORT

Bases and Aircraft that are listed below provide the coverage shown above in 50 minutes.
1 – 2 x F163 @ AFY   (Cruise Speed: 720mph - Time to Flight Level: 15 min.)
2 – 2 x F161 @ BAN   (Cruise Speed: 720mph - Time to Flight Level: 11 min.)
3 – 2 x F163 @ DAL   (Cruise Speed: 720mph - Time to Flight Level: 15 min.)
4 – 2 x F161 @ ER2   (Cruise Speed: 720mph - Time to Flight Level: 11 min.)
5 – 2 x F161 @ INC   (Cruise Speed: 720mph - Time to Flight Level: 11 min.)
6 – 2 x F161 @ MER   (Cruise Speed: 720mph - Time to Flight Level: 11 min.)
7 – 2 x F161 @ MUS   (Cruise Speed: 720mph - Time to Flight Level: 11 min.)
74.3% of the total visible area on the map is covered.

BASE COVERAGE PERCENTAGES
(AFY - F163) base is covering 26.5% of the total covered area
(BAN - F161) base is covering 33.3% of the total covered area
(DAL - F163) base is covering 22.3% of the total covered area
(ER2 - F161) base is covering 33.8% of the total covered area
(INC - F161) base is covering 27.6% of the total covered area
(MER - F161) base is covering 32.2% of the total covered area
(MUS - F161) base is covering 32.7% of the total covered area
The percentages do not sum up to %100 because there are doubly covered areas.

'NUMBER OF AIRCRAFT' COVERAGE PERCENTAGES
36.2% of the total covered area is protected with 2 aircraft
30% of the total covered area is protected with 4 aircraft
24.4% of the total covered area is protected with 6 aircraft
8% of the total covered area is protected with 8 aircraft
1.4% of the total covered area is protected with 10 aircraft
The percentages sum up to %100.

Warning: Above coverage percentages are approximate.

Figure 27 – Coverage Report for First Scenario

5.5 Scenario 2: Several Regions – Several Alert States

  The first scenario simply required coverage of the whole region with a single alert state. The tool demonstrated that, for a given set of inputs, it is able to create the backup model mentioned in Chapter 3. Further capabilities of the tool are demonstrated in the second scenario.

  For this scenario, the aircraft information, base information, compatibility table and additional constraints are the same as the first scenario; however the regions and associated alert states are different. The regions are shown in Figure 28.
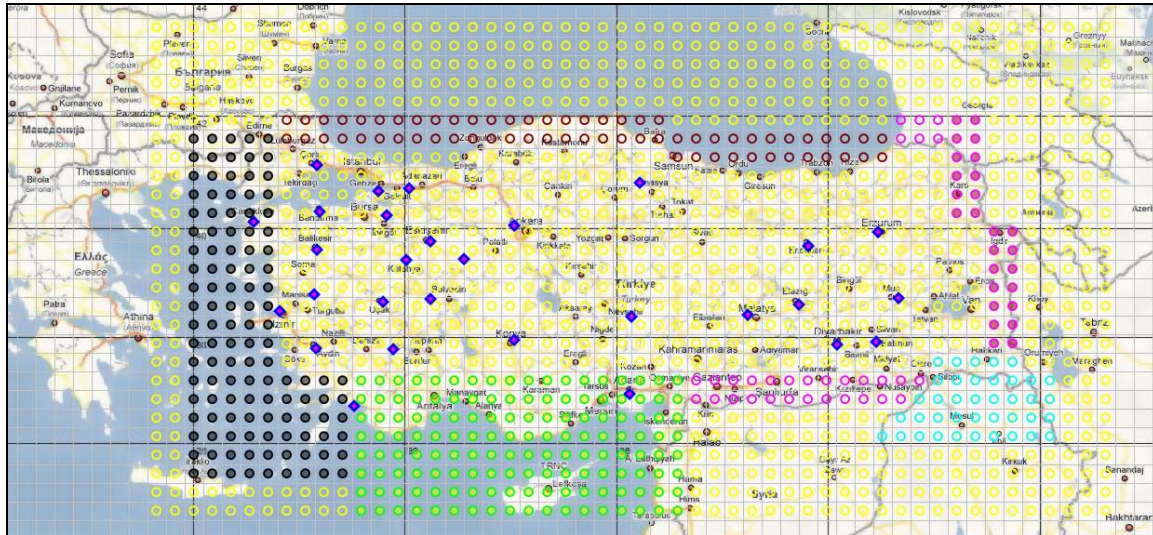
Figure 28 – Regions and Associated Alert States for Second Scenario

  Each circle's line color is the color of the primary coverage alert state; the fill color of each circle is the color of the backup coverage alert state. According to the scenario, it is necessary to protect the entire region with at least alert state 9 requirements (represented by the yellow color). The northern border of Turkey is required to be protected with alert state 3 represented (indicated by the brown color). Both the primary

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and backup coverage of the western region of the country is alert state 2, represented by the black color. Additionally, the border with the Mediterranean Sea has primary coverage of alert state 6 and backup coverage of alert state 9 (represented by yellow fill color). The eastern region of the country is protected with alert state 8 while a special region is given alert state 7. Also some area on the eastern border has backup coverage requirement of alert state 3. For the above scenario, the tool detected that all the coverage requirements cannot be satisfied, and the report in Figure 29 is produced. The user has to further analyze the problem using the report.

Figure 29 – Coverage Report for Second Scenario

As indicated in Figure 29, there are 6 groups of regions that cannot be covered. The explanations of the highlight colors are also written in the report. The first uncovered

region is in the west. The red highlight shows that neither the primary nor backup coverage requirements can be satisfied. The blue highlight occurs when both primary and backup coverage is required and only one can be satisfied. Although these might seem to be serious deficiencies, the uncoverable regions are located far a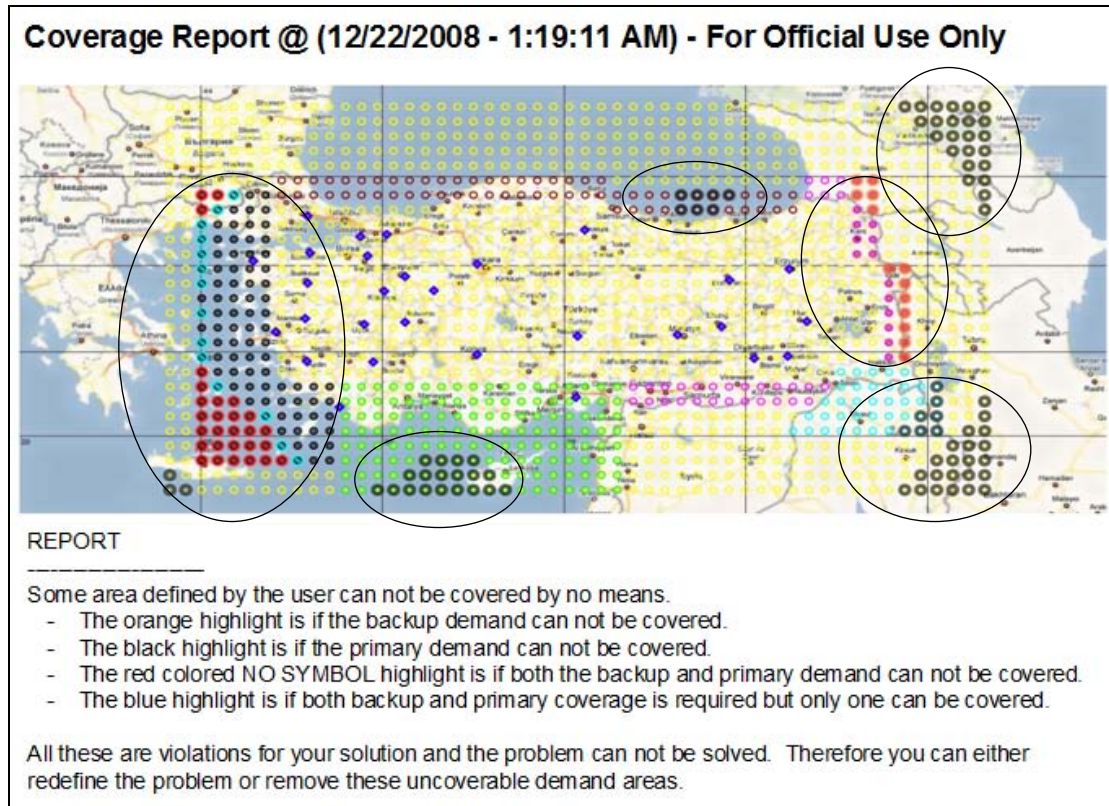way from the border; therefore, removing them may not create a serious issue in terms of air defense. The second uncoverable region is to the south. The black highlight occurs when the primary coverage cannot be satisfied. For this region, the 30 minute requirement of alert state 3 cannot be satisfied; however, this is for a small region. When the 32 minutes coverage is generated, it can be verified that the region that is highlighted is coverable in 32 minutes because it is adjacent to the covered area. Therefore, this region does not necessarily constitute a problem in terms of air defense. The third problematic region shown in the figure is in the southeastern region. Again, the uncovered area is on the outer border of the region. The fourth region that cannot be satisfied is on the eastern boundary. The orange color is present when only the backup coverage cannot be satisfied. The fifth problem area is in the northeastern part of the region. Similar to the third region, this region can also be removed because of the distance between the uncoverable regions and the border. The last uncovered area is in the northern region. The alert state 3 requirements cannot be satisfied for a small part of this region.

The regions mentioned above do not constitute a serious problem in terms of air defense. If there were a serious deficiency, the decision makers then would have to decide whether to locate the alert aircraft at civilian airbases that are close to the region or to assign less restrictive alert states for this region. For demonstrations purposes, less

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restrictive alert states are assigned to the regions that cannot be covered. After the report

is analyzed, the tool asks the user to remove the uncoverable regions. When the regions

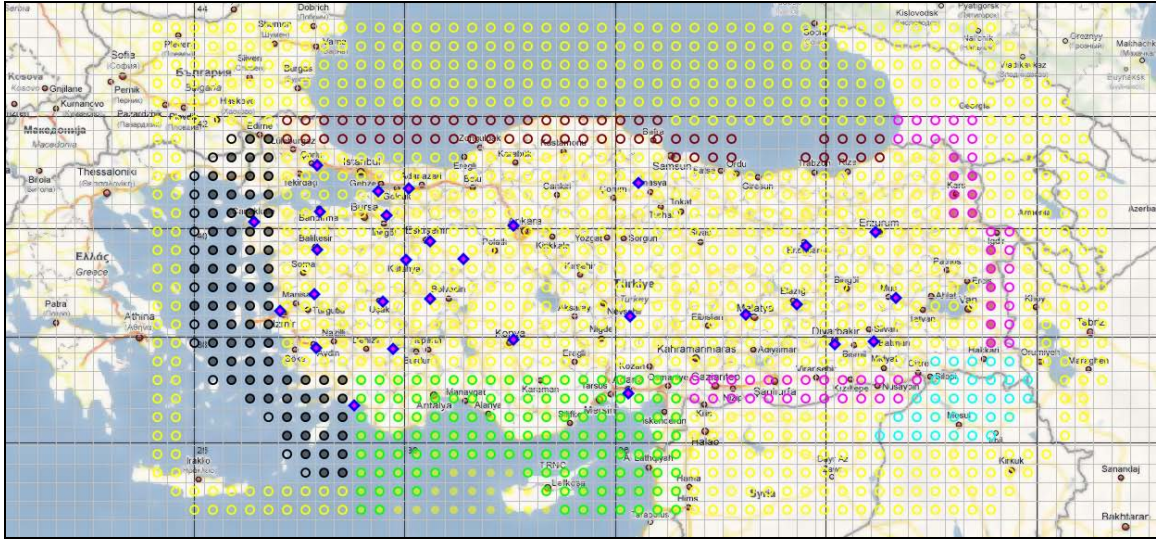are removed, the remaining demand is shown in Figure 30.

Figure 30 – Regions after the Removal of Uncoverable Area for Second Scenario
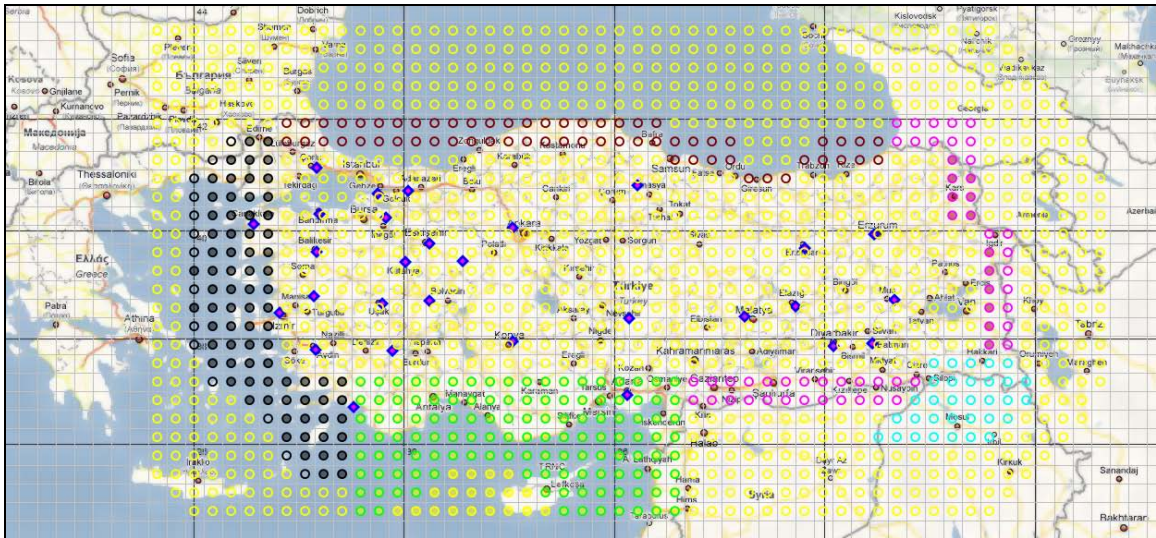
Figure 31 – Regions after the Adjustment for Second Scenario

At this point, the regions that cannot be covered are known. Therefore, the demand points in problematic regions must be readjusted with less restrictive alert states. The readjusted regions are shown in Figure 31. After this adjustment, the ARK tool generates the models and solves the problem. Unless additional constraints drive the problem to infeasibility, the set covering location problem must be feasible at this point.

The SCLP was generated in 8 minutes and 28 seconds for the second scenario. The MPS file is in Appendix I and the LINGO model is in Appendix J. The model has 25,056 variables, 25,020 of which are integer. The total number of constraints is 27,543. LINGO solved the model in 4 seconds. The solution report is in Appendix K. The model is infeasible. As has been stated, this is due to additional constraints defined by the user. The user must analyze each additional constraint and remove those that cause the infeasibility. This process is accomplished by comparing Figure 31 and Table 5. At this point, it can be seen that the upper bound of the number of aircraft at Aydin airbase is causing the infeasibility. Therefore the upper bound constraints on these bases are removed.

When the additional constraints are removed from the problem, the objective function value is 58 for SCLP. The time required to reach the solution was 4 seconds.

Once the objective function value of the SCLP model is known, the location model is generated and solved. The location model is generated in 9 minutes and 29 seconds. It required 1 second for LINGO to read the model. The MPS file is in Appendix L and the LINGO file is in Appendix M.

There are 25,056 variables, 25,020 of which are integer. The number of constraints for the model is 27,545. The model is solved in 35 seconds. The solution report is in Appendix N. The location results are listed in Table 8.

Table 8 – The Results for Second Scenario

Base	Aircraft	Base	Aircraft	Base	Aircraft	Base	Aircraft
Afyon	2xF163	Canakkale	4x_F43	Dalaman	4x_F43	Kocaeli	2xF163
Akinci	2xF161	Cigli	4xF162	Erzincan	2xF163	Konya	2xF162
Aydin	4x_F42	Cigli	4x_F42	Erzurum	2xF161	Merzifon	2xF161
Bandirma	4xF161	Corlu	4xF163	Incirlik	2xF161	Mus	4xF161
Batman	4xF162	Dalaman	4xF163	Incirlik	2x_F41		

The same set of aircraft is shown on the coverage map in Figure 32. The regions entered by the user are also shown on the map. The coverage is shown for 30 minutes. Therefore, it is expected that the regions that require 30-minute coverage must be shaded. The alert states that require 30-minute coverage are red, black and brown. As is shown, the region with primary black alert state in the west of the country, the region with primary brown alert state in the north of the country and the region with backup black alert state in the west of the country are all covered in 30 minutes. The alert states of the regions that are not shaded do not require 30-minute coverage.

Thus, the 30 minute coverage requirement for the entire region is satisfied. Using the ARK custom solution tool, the same coverage is shown in Figure 33 with each area colored with respect to how many aircraft cover the region. As is shown, the requirements for the minimum number of aircraft to cover the red, black and brown regions are satisfied.
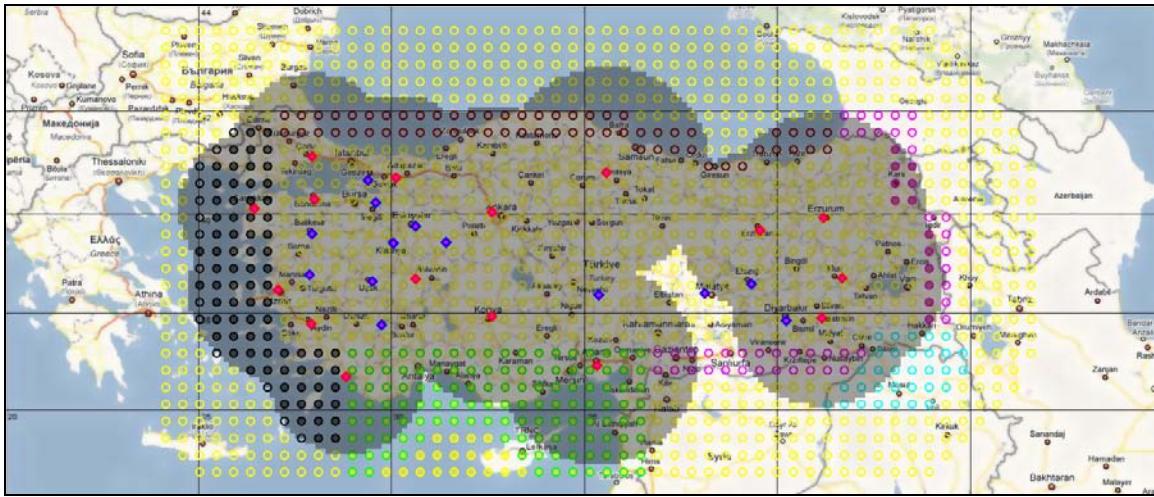
Figure 32 – 30-Minute-Coverage for Second Scenario
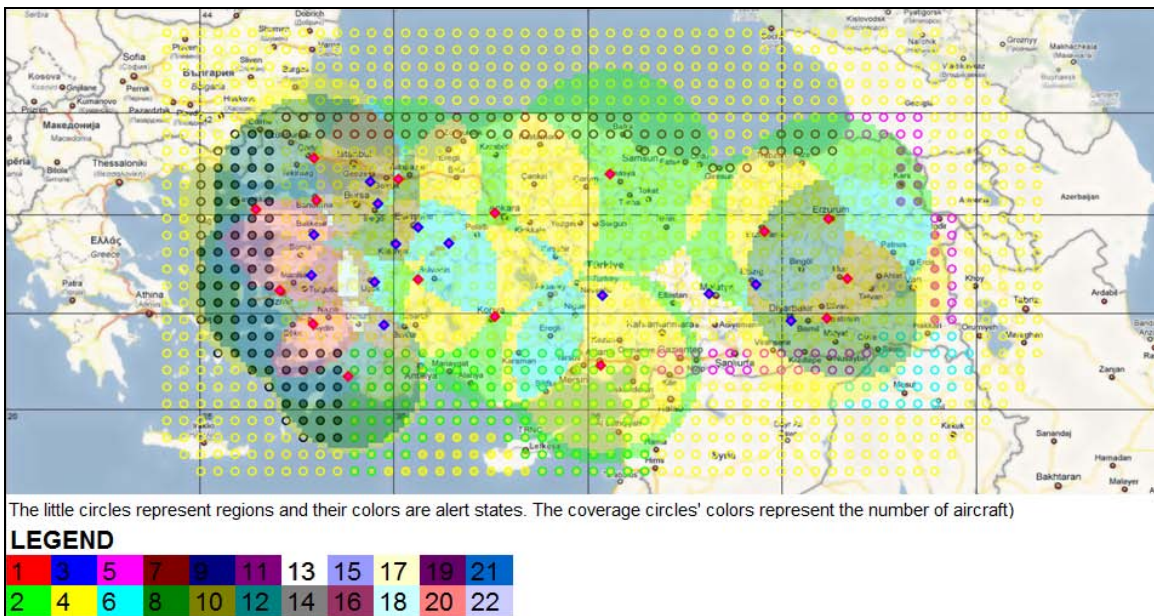
Figure 33 – 30-Minute Coverage for Second Scenario (Color Coded)

The alert states that require 35-minute coverage are orange, blue and green. In the second scenario, the region in south of the country is green. Figure 34 shows 35-minute coverage for the solution. The entire green region in the south of the country is covered.
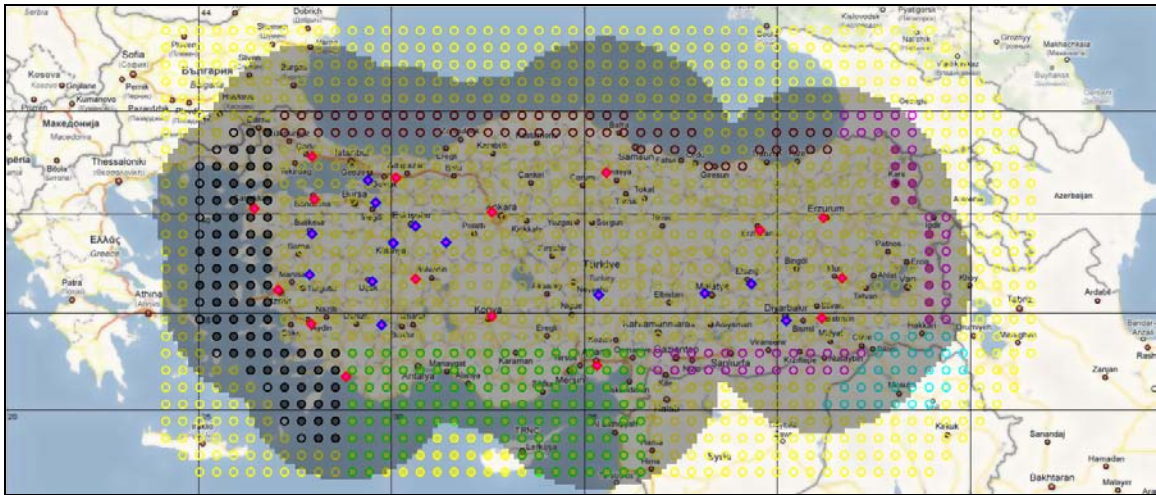
Figure 34 – 35-Minute-Coverage for Second Scenario

The alert states that require 40-minute coverage are turquoise and pink. In the second scenario, the regions in the southeastern and eastern portions of the country are pink. Additionally, there is a turquoise region in the southeastern portion as well. All these regions require 40-minute coverage. The difference between the two regions is the number of aircraft required. Figure 35 shows 40-minute coverage. As indicated, the regions with pink and turquoise alert states are covered in this figure.
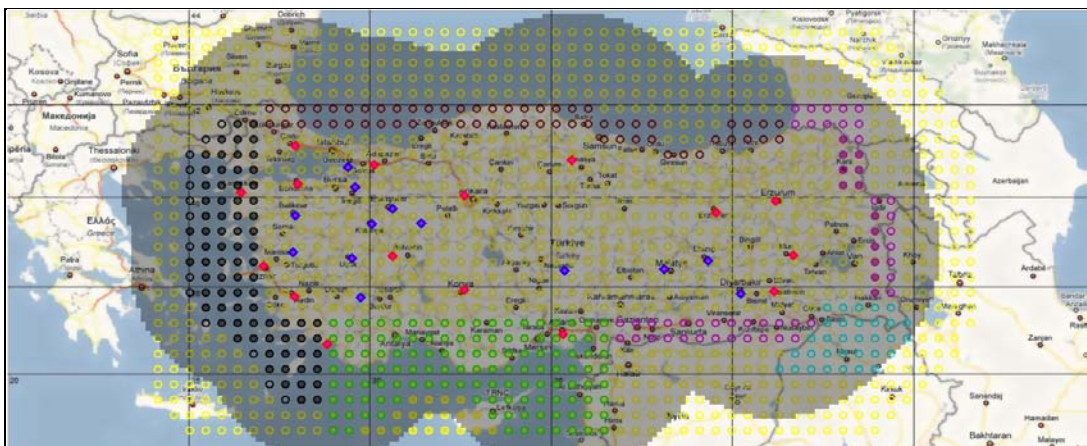
Figure 35 – 40-Minute-Coverage for Second Scenario

The remainder of the region, other than those previously mentioned, requires a yellow alert state. The yellow alert state requires 50-minute coverage. Figure 36 is the coverage map for 50-minute and the entire user-defined region is covered.
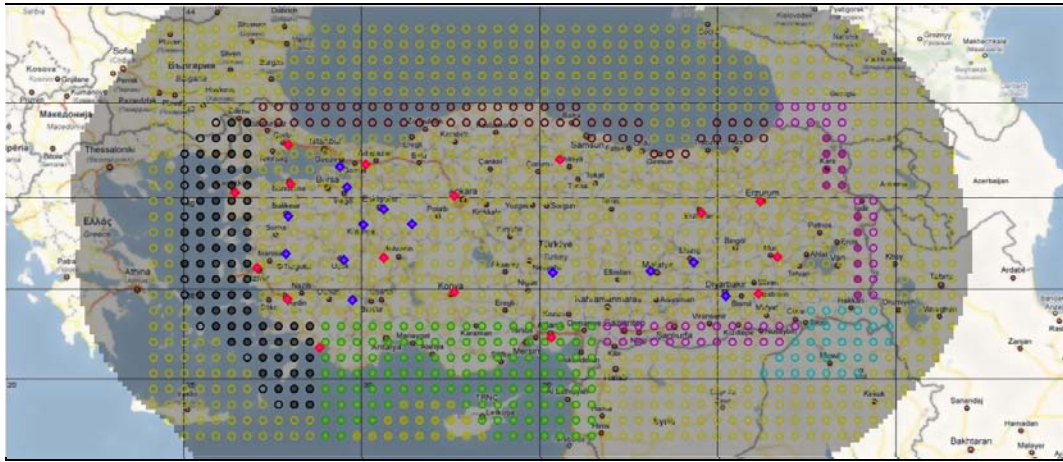
Figure 36 – 50-Minute-Coverage for Second Scenario

5.6 Scenario 3: Terrorist Attack Alarm on Major Cities

The third scenario reflects a generic intelligence update. The aircraft information, base information, compatibility table and additional constraints are identical to the first scenario.

Suppose intelligence reports indicate that terrorist attacks are anticipated in 5 of the major cities of Turkey: Ankara, İstanbul, İzmir, Bursa and Antalya. Therefore, the General Staff ordered the Air Force to cover these regions with 4 aircraft within 40 minutes from the scramble order. Upon this update from the General Staff, the Air Force has also decided to backup all the regions with the same alert state and number of aircraft. The regions and associated alert states for the third scenario are shown in Figure 37.
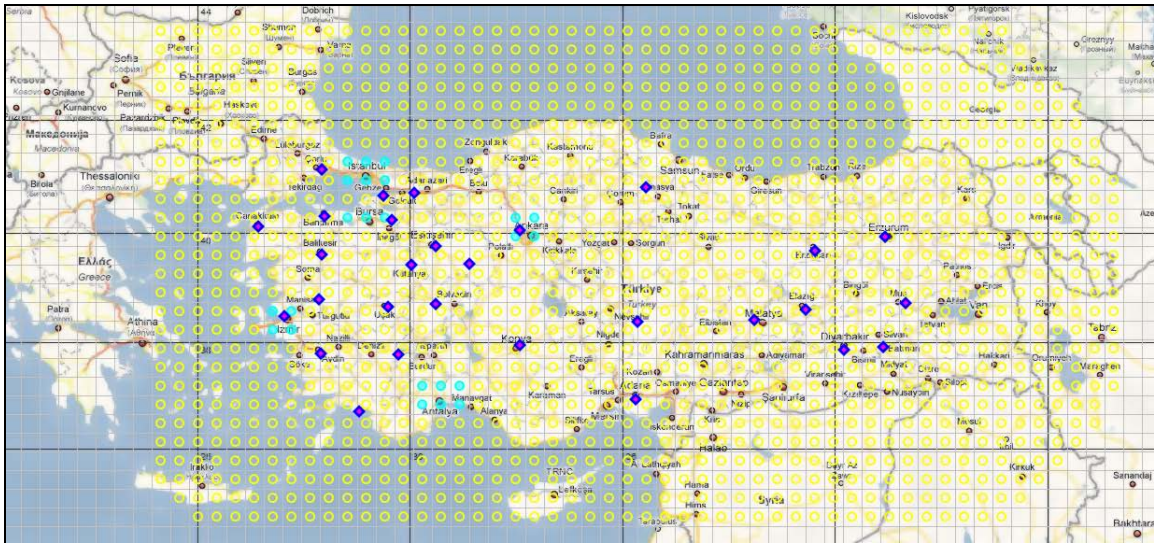
Figure 37 – Regions and Associated Alert States for Third Scenario

The model for the third scenario is generated in 9 minutes and 26 seconds. The MPS file is in Appendix O and the LINGO file is in Appendix P. The SLCP model has 27,138 variables, 27,102 of which are integer, and 29,107 constraints. The solution took 5 seconds and resulted in 28 alert aircraft. The solution report is in Appendix R.

The generation of the location model took 9 minutes and 59 seconds. The MPS file is in Appendix S and the LINGO file is in Appendix T. The model has 27,138 variables, 27,102 of which are integer and 29,110 constraints. A feasible solution was found within 1 minute, but the LINGO software could not find the optimum solution in 85 hours. The optimum solution of this model could not be obtained within a reasonable amount of time; unfortunately, this scenario requires a quick answer.

This is a temporary situation; after the anticipated threat is eliminated, the alert state will return to the state before the intelligence update. Thus, a feasible solution from the location model is sufficient for this scenario. Another feasible solution is also

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available in the SCLP model solution by looking at the same set of variables. The feasible solution from the SCLP problem is shown in Table 9.

Table 9 – A Feasible Solution for Third Scenario

Base	Aircraft	Base	Aircraft	Base	Aircraft	Base	Aircraft
Afyon	2xF163	*Cigli*	*2xF162*	Incirlik	2xF161	Mus	2xF161
Akinci	*2xF161*	*Corlu*	*2xF163*	*Konya*	*2xF162*	*Sivrihisar*	*2xF163*
Bandirma	2xF161	Dalaman	2xF163	*Kutahya*	*2xF163*		
Kayseri	*2xF162*	Erzurum	2xF161	Merzifon	2xF161		

The alert aircraft that are different from the solution of the first model are indicated using boldface and italics in Table 9. When the results of the first and the third scenarios are compared, it is apparent that the aircraft located in the first scenario are not moved to a different base. It is preferred not to deploy the existing alert aircraft, because deployment is an additional cost. Additionally, personnel are already familiar with the base and the environment.

An additional 14 aircraft are located in 7 different airbases to satisfy the additional region in the third scenario. This solution is acceptable due to the fact that the existing alert aircraft are not moved. Also, the alert aircraft required to satisfy the demand is at a minimum. The location may not be optimum in terms of total distance, but the solution is still the optimum in terms of the number of alert aircraft. The 40-minute-coverage solution is shown in Figure 38. The regions with turquoise alert state are covered with at least 4 aircraft.

The little circles represent regions and their colors are alert states. The coverage circles' colors represent the number of aircraft)

LEGEND

1	3	5	7	9	11	13	15	17	19	21
2	4	6	8	10	12	14	16	18	20	22
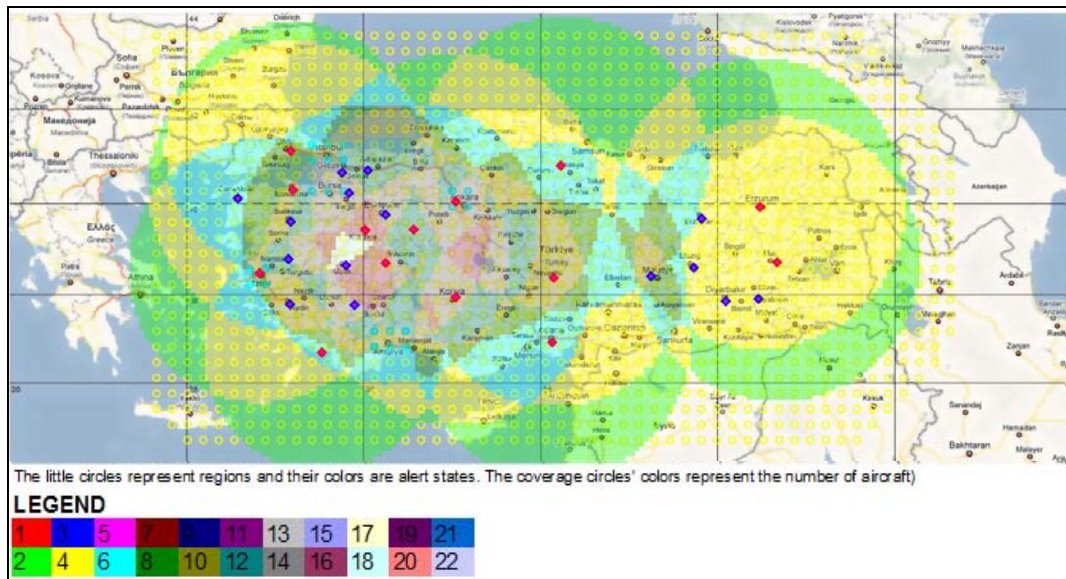
Figure 38 – 40-Minute-Coverage for Third Scenario

The entire region with yellow alert state requires 50-minute coverage. The 50-minute coverage is shown in Figure 39 and proves that the entire region is covered within the required time.

The additional airbases to the first scenario are also shown in Figure 39 with yellow circles and the airbases that were in the solution of the first scenario are shown with red circles. As is indicated, the additional airbases are all located around the newly added demand points. Thus, the aircraft that are in additional to the first scenario's solution are providing the required backup coverage.
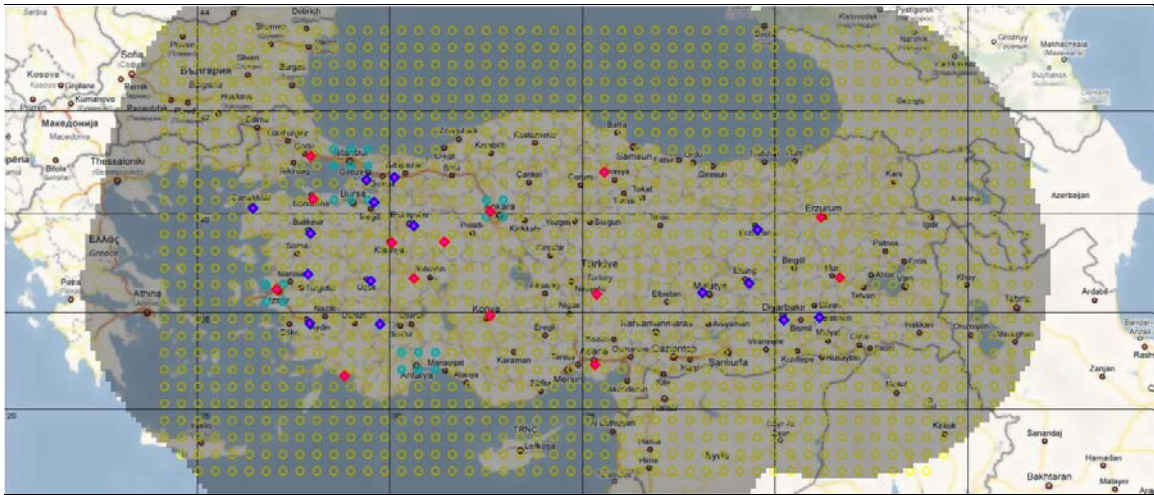
Figure 39 – 50-Minute Coverage for Third Scenario

If the feasible solution from the first model required deploying the existing

aircraft from their current bases, an alternative solution method could be followed in

order not to move the existing alert aircraft. In the alternate method, the analyst could

prefer to solve the problem only for the new demand points that are different from the

first scenario's demand points, shown in Figure 40.
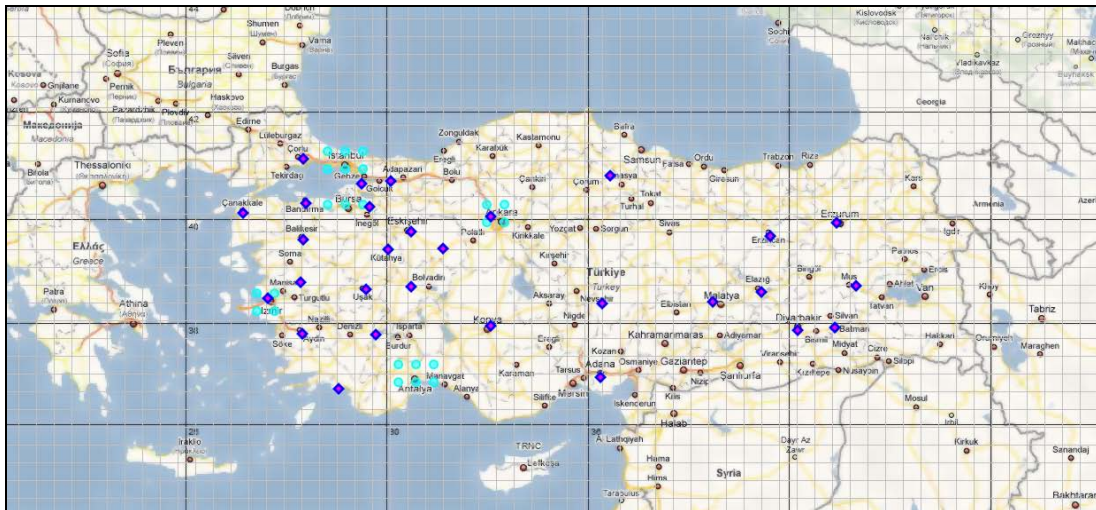
Figure 40 – Only the New Regions for Third Scenario

In this compact model, the existing aircraft would be assigned to the region with yellow alert state and the new aircraft would be assigned for the turquoise alert state. The newly located aircraft's assignment terminates after the new threat is eliminated.

The SCLP model for the compact model was created in 2 seconds. The MPS file is in Appendix U and the LINGO file is in Appendix V. The model has 1,276 variables, 1,240 of which are integer and 1,914 constraints. The solution took less than a second and the minimum number of aircraft needed to cover the new regions is 16. The solution report is in Appendix W. The location model for the same problem was created in 3 seconds. The model has 1,276 variables, 1,240 of which are integer and 1,916 constraints. The MPS file is in Appendix X and the LINGO file is in Appendix Y. The solution took 2 minutes and 32 seconds. The solution report is in Appendix Z. The results are shown in Table 10.

Table 10 – Solution for Only the New Regions for Third Scenario

Base	Aircraft	Base	Aircraft	Base	Aircraft
Afyon	2xF163	Dalaman	4xF163	Sivrihisar	2xF163
Bandirma	4xF161	Kutahya	4xF163		

The number of alert aircraft to cover the region of the first scenario is 14; therefore, the total alert aircraft to cover the entire region is now 30. This is 2 more alert aircraft than the optimum value. Although 2 more alert aircraft are required for this solution, recall that this is a temporary assignment. Therefore, the decision makers could prefer to assign 2 more aircraft than the optimum, rather than relocating the entire alert aircraft network.

The combined solution of Table 10 and Table 7 is shown in Table 11. This solution requires 30 aircraft located at 9 airbases.

Table 11 – Combined Solution of Third Scenario

Base	Aircraft	Base	Aircraft	Base	Aircraft
Afyon	4xF163	Erzurum	2xF161	Merzifon	2xF161
Bandirma	6xF161	Incirlik	2xF161	Mus	2xF161
Dalaman	6xF163	Kutahya	4xF163	Sivrihisar	2xF163

The 40-minute coverage for the combined solution is shown in Figure 41. All 5 cities under terrorist threat are covered with at least 4 primary and 4 backup alert aircraft.
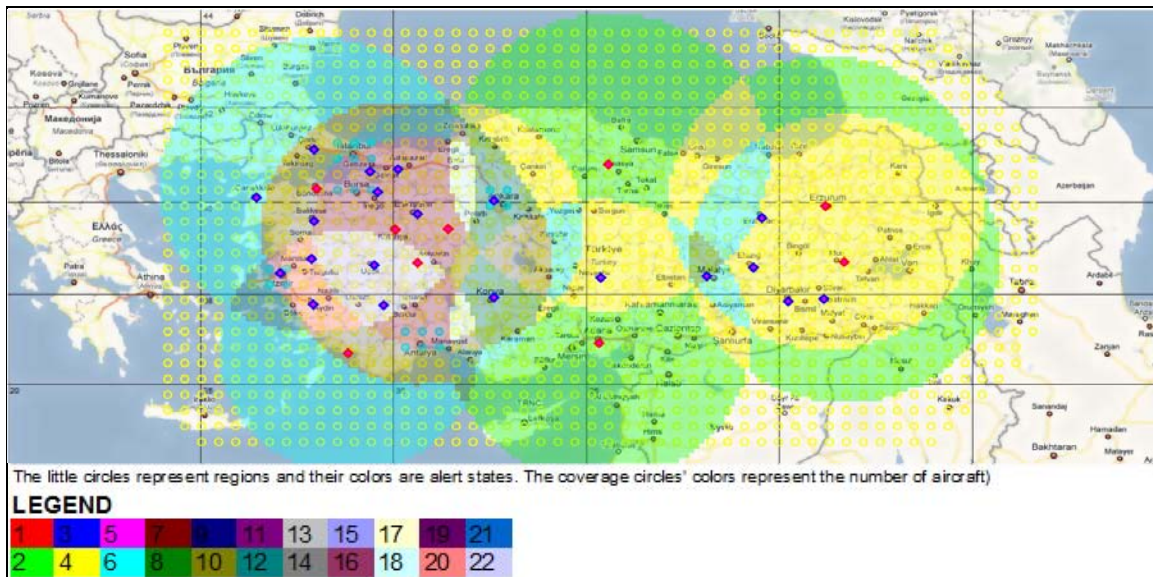
Figure 41 – 40-Minute-coverage for Third Scenario for the Alternate Solution

The 50-minute coverage is shown in Figure 42. The entire region is covered.
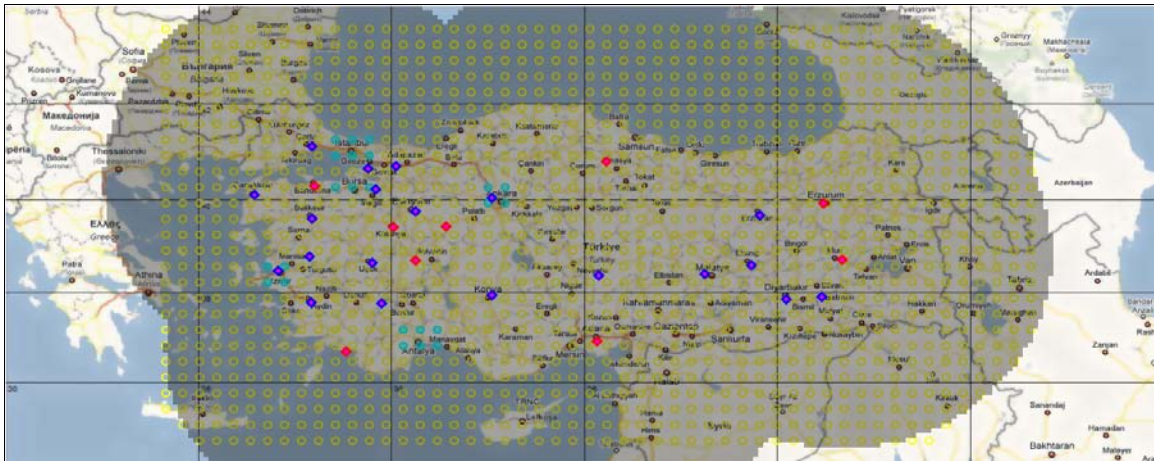
Figure 42 – 50-Minute-coverage for Third Scenario for the Alternate Solution

The solution of the third scenario demonstrated 2 different solution approaches. The first was to build the models as in the first and second scenarios and solve them. Because the location model did not give an optimal solution within a reasonable amount of time, the user can use a feasible solution instead of the optimum location; the feasible solution did not require moving the existing alert aircraft.

The feasible solution could have required moving the existing aircraft. An alternate approach was proposed for the case where aircraft are not moved. The user could partition the problem; the first portion was exactly the same as the first scenario and the second portion is the newly added regions around the cities where the terrorist attacks are anticipated. This alternate solution required 2 more aircraft than the optimal solution required.

The user could build several different models within a short time period and find solutions. The comparison of these solutions could lead to the best solution in terms of air defense.

5.7 Summary

Three selective scenarios are modeled and solved in this chapter. The tool demonstrated the ability to model the problems. Most problems were solved in less than a minute. The solutions of the models were reasonable in terms of air defense. Thus, using the models generated by the tool represents the problems that the user defined using the tool, and the solutions provided are the optimum locations for the alert aircraft.

VI. Conclusions and Recommendations

6.1 Summary of the Research

This research developed a tool for the location optimization of alert aircraft with changing threat anticipation. First, a location model is formulated; then this formulation is implemented in a tool. The tool is capable of modeling different airbases, aircraft, alert states and regions as well as additional constraints.

The first chapter introduced the research objectives and reviewed the scope, limitations and the assumptions for the research. The literature review chapter discussed location problem types, the modeling structures and the solution techniques. Similar past studies in the literature were also reviewed.

The model structure, solution technique and the coding tools were presented in the methodology chapter. The mathematical model and the tool's pseudocode were presented in the third chapter.

The fourth chapter presented a guide for the users of ARK tool. The abilities of the tool are reviewed in this chapter. Validation of the methodology and the tool were done in the results and analysis chapter. Three selective scenarios were analyzed in this chapter. Scenario models were generated using the tool. The final chapter is the conclusion chapter. The final comments about the tool and some recommendations for future research on the subject are made.

The objective of this research was to develop a tool that answers the question: *What is the optimum location of the alert aircraft such that the number of aircraft is minimized and the alert network objective is met?*

The ARK tool, developed in this research, finds an answer for the above question for different user-defined circumstances. The tool is flexible in adding, changing or deleting alert states, regions, aircraft and airbases which makes it adaptable to threat anticipation changes.

6.2 Conclusions

In this research, a location model is formulated and a user friendly tool was developed. The location model is capable of handling backup coverage as well as primary coverage as a requirement. The model also does not allow the aircraft that satisfy the primary coverage of an area to be assigned for the backup coverage for the same area. A different set of aircraft from a different location must be assigned to backup coverage. However, the aircraft assigned for the primary coverage of an area can be assigned for the backup coverage of a different area.

The research develops an approach that models backup coverage. More than one service can be located at a candidate point and the demand points may require more than one service. Therefore, coverage is satisfied when the required level of service exists at the candidate points that cover the demand point.

This tool is an aid for the air defense officers who help the decision makers select alert aircraft location. When analyzing the situation and trying to optimize alert aircraft location, the tool could be used as a means of visualizing and comparing the alternative solutions as well as optimizing the performance parameters.

The decision makers must include not only the performance considerations but also several other inputs. After a solution is generated, the real location of the alert aircraft will depend on these other considerations (political, economic, etc concerns).

6.3 Recommendations for Future Research

When an alert aircraft is scrambled, the area of responsibilities of the remaining alert aircraft could possibly change. The area that was covered by the scrambled aircraft must be covered in case of another incident in the same area. Future research could include the assignment of this area to different bases or possible relocation of the existing alert aircraft.

Only the performance considerations for the optimum location of the alert aircraft are included in this research. Future research may consider an application of decision analysis methods with cost analysis included.

The stochastic nature of the threat is not included in the research. According to historical data, probabilities of threat could be built and the location of the alert aircraft could depend on the probabilities of the anticipated threat and the risk.

Additionally, the decision makers might prefer to trade the number of alert aircraft with coverage; therefore, the objective function of the existing model could be modified to include this situation.

Appendix A: Coordinate Regression Analysis Data Points and Results

#	Name	X	Y	LAT	LON	PRED LAT	PRED LON	Error (Miles)
				Analysis Set				
1	X 11	172.5	94.5	42.00	25.00	41.98	25.01	1.24
2	X 12	342.8	94.5	42.00	30.00	41.98	30.00	1.07
3	X 13	513.8	94.5	42.00	35.00	41.98	35.01	1.08
4	X 14	684	94.5	42.00	40.00	41.98	39.99	1.01
5	X 15	855	94.5	42.00	45.00	41.98	45.00	0.89
6	X 21	172.5	185.3	40.00	25.00	39.98	25.01	1.44
7	X 22	342.8	185.3	40.00	30.00	39.98	30.00	1.28
8	X 23	513.8	185.3	40.00	35.00	39.98	35.01	1.27
9	X 24	684	185.3	40.00	40.00	39.98	39.99	1.19
10	X 25	855	185.3	40.00	45.00	39.98	45.00	1.05
11	X 31	172.5	273	38.00	25.00	37.98	25.01	1.19
12	X 32	342.8	273	38.00	30.00	37.98	30.00	1.02
13	X 33	513.8	273	38.00	35.00	37.98	35.01	1.03
14	X 34	684	273	38.00	40.00	37.98	39.99	0.97
15	X 35	855	273	38.00	45.00	37.98	45.00	0.84
16	X 41	172.5	358.5	36.00	25.00	35.98	25.01	1.16
17	X 42	342.8	358.5	36.00	30.00	35.98	30.00	0.98
18	X 43	513.8	358.5	36.00	35.00	35.98	35.01	1
19	X 44	684	358.5	36.00	40.00	35.98	39.99	0.94
20	X 45	855	358.5	36.00	45.00	35.98	45.00	0.82
21	Aksaray	480	255.8	38.36	34.01	38.38	34.02	1.25
22	Alanya	410.3	334.5	36.53	31.97	36.55	31.97	1.4
23	Bursa	309.8	175.5	40.18	29.05	40.20	29.03	1.67
24	Grozni	877.5	33	43.29	45.66	43.31	45.66	0.65
25	Erzincan	666	195.8	39.72	39.46	39.74	39.47	1.05
26	Halep	585.8	348.8	36.19	37.13	36.21	37.12	1.81
27	Kars	789	156.8	40.60	43.07	40.61	43.07	0.92
28	Kerkük	834	380.3	35.44	44.38	35.47	44.39	1.21
29	Kırşehir	484.5	222	39.13	34.15	39.15	34.15	1.18
30	Tebriz	897.8	268.5	38.07	46.27	38.09	46.26	1.65

	Analysis Set (continued)							
#	Name	X	Y	LAT	LON	PRED LAT	PRED LON	Error (Miles)
31	Trabzon	674.3	139.5	40.98	39.70	41.00	39.71	0.93
32	Varna	270.8	37.5	43.20	27.88	43.21	27.89	0.81
33	Ankara	439.5	186.8	39.93	32.83	39.95	32.83	1.12
34	Burgaz	255.8	71.25	42.47	27.44	42.49	27.45	0.9
35	Izmir	243.8	253.5	38.39	27.11	38.43	27.10	2.68
36	Rize	701.3	138.8	41.00	40.50	41.01	40.50	0.92
37	Trablus	541.5	422.3	34.43	35.82	34.46	35.82	1.36
38	Hakkari	811.5	290.3	37.56	43.73	37.58	43.73	1.13
39	Iraklio	175.5	387.8	35.32	25.11	35.29	25.10	2.25
40	Bandırma	273	168.8	40.33	27.95	40.35	27.95	1.13

The average error is 1.284 miles and standard deviation is 0.447 miles for the 70 data points in analysis and verification data sets.

Prediction Expression for LAT

$$LAT = 44.1929623846697 - 0.0227147515606417 * Y + (Y - 225.58125) * ((Y - 225.58125) * -0.0000037152211770226)$$

Prediction Expression for LON

$$LON = 19.9551967395451 + 0.0292965454361673 * X + (X - 524.83) * ((X - 524.83) * -0.000000016538264477)$$

Where,

LAT = Latitude

LON = Longitude

X = Distance from left end of the screen (in pixels)

Y = Distance from top of the screen (in pixels)

						PRED	PRED	Error
#	Name	X	Y	LAT	LON	LAT	LON	(Miles)
1	Antalya	366	319.5	36.86	30.67	36.90	30.68	2.44
2	Atina	127.5	273	37.96	23.69	37.98	23.69	1.41
3	Bafra	543.8	113.3	41.56	35.88	41.57	35.89	0.92
4	Erzurum	726.8	188.3	39.89	41.24	39.91	41.25	1.01
5	Eskisehir	360	194.3	39.76	30.50	39.78	30.50	1.17
6	Canakkale	219.8	177.8	40.13	26.39	40.15	26.39	1.17
7	Cankiri	465.8	157.5	40.58	33.60	40.60	33.60	1.05
8	Cizre	758.3	301.5	37.30	42.17	37.32	42.17	1.19
9	Diyarbakir	690.8	275.3	37.89	40.21	37.93	40.19	2.43
10	Erbil	821.3	350.3	36.16	44.01	36.18	44.01	1.21
11	Igdir	822	188.3	39.89	44.03	39.91	44.04	0.97
12	Isparta	361.5	282.8	37.74	30.54	37.76	30.55	1.35
13	Kahramanmaras	578.3	289.5	37.56	36.91	37.60	36.90	2.53
14	Van	798.8	249.8	38.48	43.35	38.52	43.36	1.94
15	Zonguldak	403.5	119.3	41.43	31.77	41.44	31.78	0.98
16	Istanbul	306.8	138.8	41.00	28.96	41.01	28.94	1.61
17	Konya	427.5	277.5	37.86	32.48	37.88	32.48	1.32
18	Malatya	625.5	256.5	38.32	38.30	38.36	38.28	2.44
19	Maraghen	896.3	298.5	37.37	46.21	37.39	46.21	1.11
20	Mus	734.3	240	38.72	41.46	38.74	41.47	1.11
21	Musul	791.3	343.5	36.32	43.13	36.34	43.14	1.22
22	Nevsehir	503.3	245.3	38.60	34.69	38.62	34.70	1.22
23	Nigde	501.8	273.8	37.94	34.65	37.97	34.65	1.28
24	Rodos NE point	282	339.8	36.44	28.19	36.43	28.22	1.92
25	Samsun	558	126	41.28	36.32	41.29	36.30	1.55
26	Selanik	101.3	156	40.61	22.92	40.63	22.92	1.14
27	Sivas	582	195.8	39.72	37.00	39.74	37.01	1.09
28	Sochi	674.3	18.75	43.60	39.70	43.61	39.71	0.68
29	Sofya	114	61.5	42.68	23.31	42.70	23.29	1.53
30	Soke	253.5	282.8	37.74	27.38	37.76	27.38	1.39

Verification Set

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14. ABSTRACT

The threat to the airspace is posed by the outside world in conventional terms as well as hostilities from within the airspace such as hijacked aircraft. Alert aircraft are located with the sole responsibility of responding to any incident.

Different regions of the airspace may have different alert states depending on current intelligence input. Due to non-constant states of threat level, the Turkish Air Force must deploy aircraft to cover the more sensitive regions with a greater number of aircraft with a relatively short response time.

This research deals with the problem by developing a tool for the location optimization of the alert aircraft. The tool can adapt to changes in threat anticipation while meeting the objectives of the alert network. Thus, a new location model with backup coverage requirements was formulated, and an interactive tool is developed that is capable of generating the aircraft locations for different user-defined threat anticipation.

15. SUBJECT TERMS
Mixed, Integer Programming, Location, Optimization, Backup, SCLP, *P*-Median, *P*-Center, Coverage, Coordinate, Regression, Alert, Aircraft, Scramble

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